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LEACHING AND OIL FILL SCHEDULES FOR THE STRATEGIC PETROLEUM RESERVE (SPR)

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ABSTRACT

This report discusses the leaching and oil fill schedules of, caverns being developed for the Strategic Petroleum Reserve program. In particular, detailed schedules for the Phase II development at Bryan Mound and West Hackberry are presented. The techniques used to develop these schedules from the computer-based simulations of the leaching process are discussed. Finally, methods for leaching the caverns in ways that maintain the maximum flexibility as to the amount of oil required are presented.

Acknowledgment

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FOR THE STRATEGIC PETROLEUM RESERVE (SPR)

Introduction

As a part of the Strategic Petroleum Reserve program storage caverns will be developed at a number of sites. These caverns will be leached in salt domes, and each cavern will hold ten million barrels (MMB) of oil. This report discusses the schedules for leaching and filling of these caverns. The following topics are addressed.

- A schedule for the planned Phase II development at Rryan Mound and West Hackberry is presented.

- The techniques used to develop these schedules are discussed in detail. These techniques can be used to evaluate alternative leaching plans and to update the Phase II schedule based on actual performance.

- Methods for leaching the storage caverns in a way that maintains the maximum flexibility as to the amount of oil required are discussed. Specifically, the conversion from a leach-then-fill to a leach/fill strategy is developed.

Schedule for Phase II of SPR

Phase II of the SPR program calls for the leaching of 12 caverns at Bryan Mound and 16 at West Hackberry. This will give a maximum oil storage capacity of 280 MMB. Half of the caverns at each site will be leached at one time, and the other half will be leached after the first group has been completed. The schedules are expressed in terms of the total leached volume, the volume available for oil storage, and the rate of oil delivery on a quarterly basis starting in 1980 and continuing until Phase II is completed in 1986. The start and completion dates for the caverns are summarized in Table 1.

Table 1 Baseline Start and Completion Schedules for Phase II Caverns for SPR*

	Start of Leaching	Start of Significant Oil Fill	End of Leaching
Bryan Mound			
Group 1			
2 caverns	3/80	8/81	1/83
4 caverns	7/80	12/81	5/83
Group 2			
2 caverns	1/83	6/84	11/85
4 caverns	5/83	10/84	3/86
West Hackberry			
Group 1			
8 caverns	5/81	8/82	10/83
Group 2			
8 caverns	10/83	2/85	4/86

*This schedule applies to a leach/fill strategy. For a leach-then-fill strategy the Group 1 caverns will be completed about two months sooner and the Group 2 caverns will be completed about four months sooner. The above schedule does not include the time to fill the cavern to capacity.

Two leaching strategies are examined--a leach-then-fill and a leach/fill. The leach-then-fill strategy allows the leaching of the cavern to be completed with the minimum amount of oil: about 0.25 MMB per cavern. The leach/fill strategy allows storage of oil at the earliest possible time.

The oil volume and the oil flow rate data have maximum and minimum values. The minimum values are the minimum amounts of oil required to leach the caverns, and the maximum values are the maximum volume available for oil storage. (At the end of the leaching, a storage cavern contains only a portion of its ten million barrel oil capacity: 68 percent for a leach/fill and less than three percent for a leach-then-fill strategy. The maximum available volume data assumes that the caverns are filled to capacity at the site design fill rate - 240,000 barrels/day for Bryan Mound and 175,000 barrels/day for West Hackberry. The minimum oil required data adds no more oil after the end of leaching.)

The total leached volumes and the oil volumes are plotted versus time in Figure 1 (all of Phase II), Figure 2 (Bryan Mound only) and Figure 3 (West Hackberry). The data from which these figures are derived are tabulated quarterly in Tables 5, 6 and 7 on pages 23, 24 and 25 of this report. The assumptions used in deriving these schedules are summarized in the next section and detailed in Appendix A.

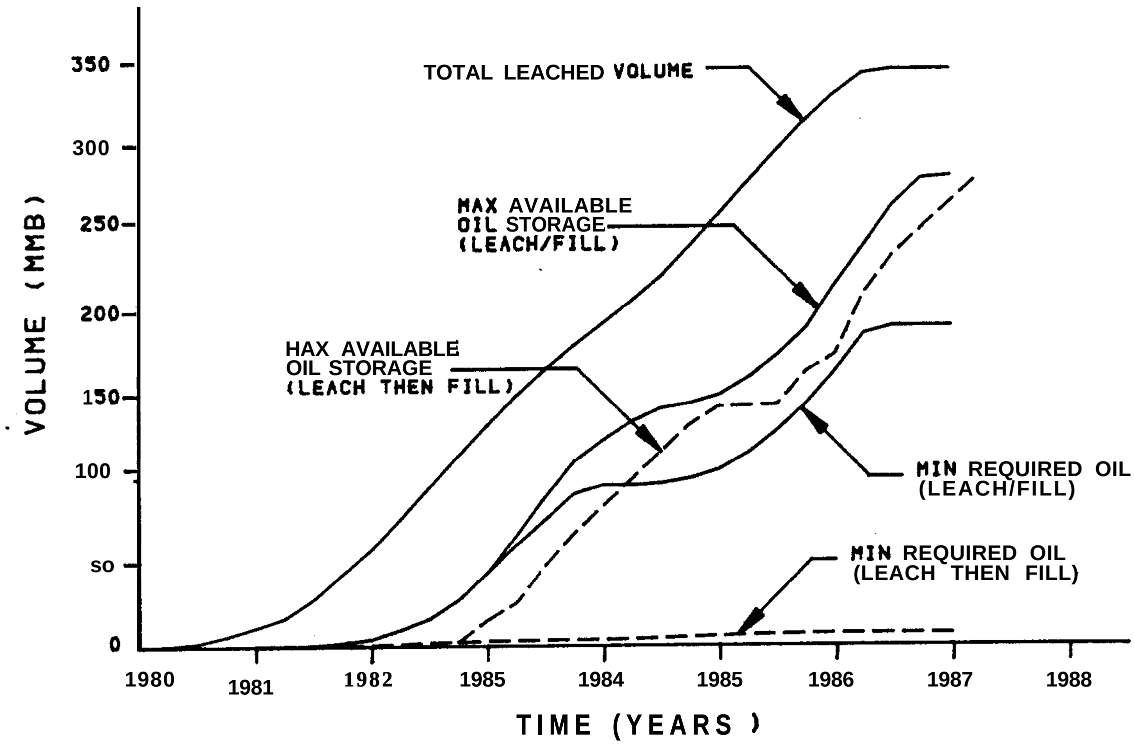

FIG 1 TOTAL LEACHED VOLUHE AND OIL VOLUHE VERSUS TIME
BRYAN HOUND & WEST HACKBERRY

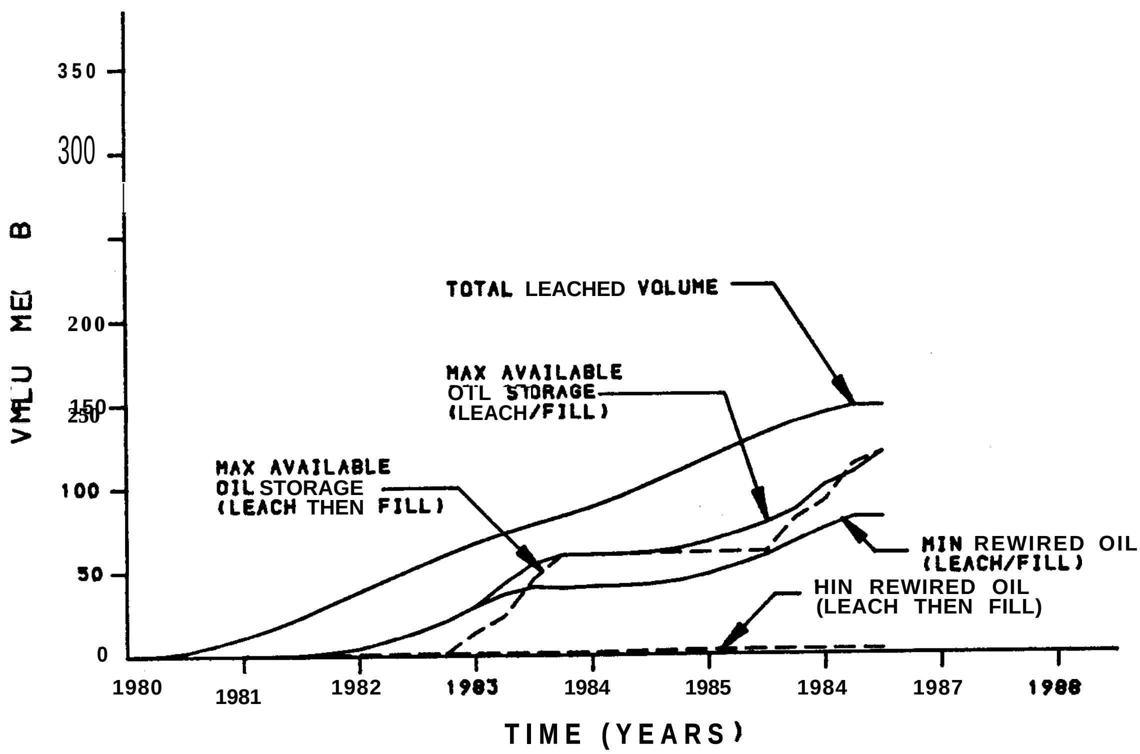

FIG 2 TOTAL LEACHED VOLUHE AMD OIL VOLUHE
BRYAN HOUND ONLY

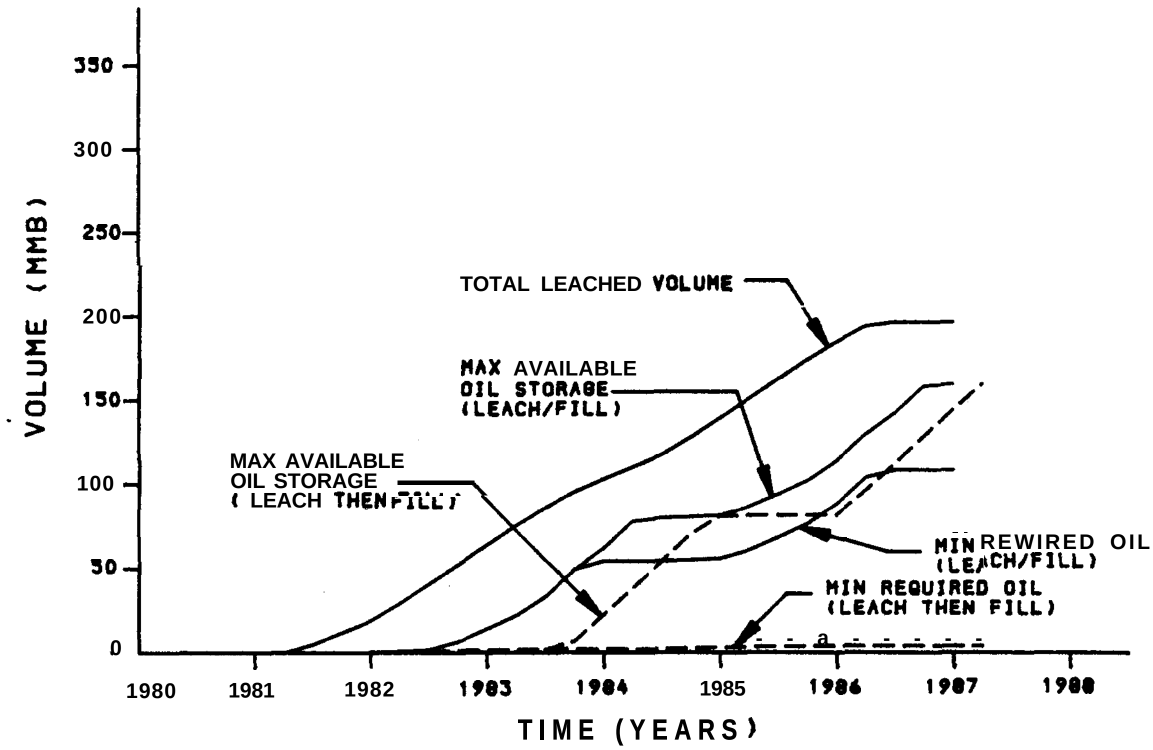

FIG 3 TOTAL LEACHED VOLUME AND OIL VOLUME
WEST HACKBERRY ONLY

While considerable effort has been devoted to making the schedules as accurate as possible, the total leached volume is accurate to no more than + 5% and the oil volume to no more than + 10%. These accuracies presume that the basic assumptions (such as the start dates for leaching, number of caverns leached, and the maximum brine disposal rate) used in deriving the schedules do indeed apply to the actual leaching. There are at least two sources of uncertainty.

- The schedules uses a computer code to simulate the cavern leaching. The code, in turn, assumes typical solubilities for the salt. The salt solubilities encountered in the actual leaching will differ from the assumed values which will cause the cavern to grow at a rate faster or slower than predicted.

. The ideal times derived from the computer simulation are arbitrarily derated by an assumed contingency factor of 10% and a 60-day delay in sump development. These factors affect the oil volume curve by 25% (Appendix B). If the actual performance varies significantly from the assumed contingencies, the actual schedule will differ from the predicted.

The accuracy of the predicted schedules can be improved if the actual performance is used to update the model. Techniques for using actual performance to update the model are discussed in Appendix C. These techniques are illustrated by using actual performance up through September 9, 1980 to update the prediction for leaching the Group 1 caverns at Bryan Mound. This exercise indicates that the actual performance is on schedule at least as of September 9, 1980.

Schedule Development

The first step in developing the schedules is to simulate the leaching process using the SALT 77 computer code developed by Ahmad Saberian for the Solution Mining Research Institute. The simulation assumed one direct leach phase to create the sump/chimney and three reverse leach phases to create the main body of the cavern. The final cavern has a total leached volume of 12.3 MMB: 10 MMB for oil storage, 1 MMB for a brine buffer, and a 1.3 MMB sump for insolubles. The cavern is shaped like a flower pot with a diameter of 230 feet at the top and a diameter of 170 feet 2000 feet below the top. (The leaching simulation and the other facets of schedule development are discussed in more detail in Appendix A.)

The simulation assumed a three-well slick hole approach. The three wells are leached simultaneously during the sump/chimney phase. For the reverse leaching phases the center tubing is removed from the three wells, one of the wells is selected for raw water injection and the other two are used for brine production. This approach is consistent with the plans for the Group 1 caverns at Bryan Mound. However, sufficient simulation of other configurations (ranging from the leaching of a single well to the simultaneous leaching of three wells) have been performed to determine that the configuration has little impact on the leaching schedule. Based on these ideal simulations it will require 665 days at a brine production rate of 136 MB/D to leach a cavern using a leach-then-fill strategy and 715 days using a leach/fill strategy.

These idealized leaching times must be modified to reflect actual performance. Workover times must be included, the times must be adjusted for flow rates other than 136 MB/D, the contingency factor and the sump delay must be included, and finally the time to fill the caverns to capacity must be included. These factors that modify the ideal leach schedule are summarized in Table 2.

Table 2 Assumptions

	Bryan Mound		West Hackberry
Number of caverns Group l/Group 2	6/6		8/8
Brine Production Rate per Cavern	113 MB/D		136 MB/D
Maximum oil delivery Rate to the Site	240 MB/D		175 MB/D
Sump Delay Group l/Group 2		60 days/60 days	
Contingency		10 percent	
Start Dates			
(Group 1)	2 caverns on 3/10/80 4 caverns on 7/20/80		8 caverns on 5/1/81
(Group 2)		On completion of one or more caverns in Group 1.	
Workover Times	58 days		58 days

These factors have been used in other schedule developments, with the possible exception of applying 60-day sump delay to the Group 2 caverns. Originally this delay (often called "startup delay") was meant to cover problems unique to the startup of a leaching operation including delays in completing construction. However, based on the startup of Bryan Mound, a 60-day contingency should be added to the sump/chimney phase to allow for the problem of plugged wells. The plugging is unique to the sump/chimney stage because water is being injected below the level of the insoluble pile. If circulation is lost the sand can back flow into the injection string and plug the well. The back flow is caused by faulty check valve operation and the brine/fresh water differential head. In some cases, unplugging of the well is a very time-consuming operation. Plugging of Group 2 wells may be somewhat less frequent because circulation should be lost less frequently. However, plugging will occur and it is assumed that the time consumed in unplugging them will be comparable to the Group 1 caverns. Based on the above arguments, a 60-day contingency should be included during the sump/chimney stage for both Groups 1 and 2. This only takes into account delays encountered after leaching is started. Delays caused by slips in the construction will have to be factored in separately.

Realistic schedules (Table 3) for the leaching of single caverns were developed using the results of the simulations and the

Table 3 Cavern Development Chronology

	End of Sump/Chimney (days)	End of Roof Development (days)	End of Leaching (days)	Cavern Filled* to Capacity (days)
Bryan Mound				
Leach/Fill	290	520	1040	1120
Leach-Then-Fill	290		960	1205
West Hackberry				
Leach/Fill	265	465	910	1055
Leach-Then-Fill	265		855	1300

*Filling rate is 40 MB/D at Bryan Mound and 22 MB/D at West Hackberry assumptions in Table 2. These schedules for single caverns were then combined to give the overall leaching schedules summarized in Tables 5, 6, and 7. The combining of the single cavern schedules was accomplished using a computer program which is described in Appendix F.

A number of other schedules have been developed for the leaching of the SPR caverns. All these alternate schedules, with the possible exception of one, are known to be based on simulation codes developed by Ahmad Saberian. Their total leaching volume and oil volume curves are compared in Appendix D. The total leached volumes agree well. However, there are significant differences in their oil volume curves. In most cases these differences can be traced to different assumptions in the leaching simultions or to different contingency factors.

Flexibility in Oil Requirements

The minimum required oil shown in Figures 1, 2, and 3 and Tables 5, 6, and 7 is necessary for leaching of caverns with the desired shape and volume. If the oil requirements are not met, the caverns will be misshapen. Unfortunately the quantity of oil available for storage will be influenced by factors other than the needs of the leaching program. Therefore the leaching of the caverns may have to proceed with whatever oil is available. This section will discuss techniques for accommodating oil volumes that lie between the maximum oil volume that can be stored using a leach/fill strategy and the minimum oil required for a leach-then-fill strategy. These techniques are limited to those that maintain the cavern shape. They do not provide unrestricted flexibility to adopt any oil volume curve that lies between the extremes. The three approaches are discussed below.

Conversion from Leach-Then-Fill to Leach/Fill -- The leaching strategy can be converted from leach-then-fill to Leach/fill at any time without degrading the cavern shape. The following observations can be made about such conversions:

1. The sump-chimney phases for both strategies are identical. Therefore the decision as to which strategy to adopt can be delayed until the end of the sump-chimney phase.

2. Before a cavern can accept significant amounts of oil, the cavern roof must be completed to the desired diameter. The leach/fill strategy accomplishes this as quickly as possible by injecting raw water close (within 250 feet) to the cavern top until the roof is complete. The leach-then-fill strategy develops the roof more gradually so that the completion of roof development coincides with cavern completion. Conversion from leach-then-fill to leach/fill will involve resetting the raw water injection strings to positions close to the roof.

3. The length of time from the start of leach to start of significant oil injection (which is equivalent to roof completion) is a minimum when a leach/fill strategy is selected at the end of sump-chimney. The time between the start of leach and the start of oil injection increases the longer the decision to convert is delayed past the completion of sump-chimney. However, the time between the decision to convert and the start of oil injection decreases.

4. While converting from leach-then-fill to leach/fill will delay the start of oil injection, the time required to complete the cavern does not change. This means that the average rate of oil injection during the final leach/fill phase of a converted cavern increases.

The conversion parameters are summarized in Table 4.

The ability to convert from a leach-then-fill to a leach/fill strategy increases the flexibility of the system. If a leach/fill strategy is adopted and there is not enough oil to meet minimum required for this option, continued leaching at the design rate may result in misshapen caverns. If leaching is stopped in any cavern because of lack of oil, the rate of oil fill, when and if the oil becomes available again, will be the same as when leaching was stopped. On the other hand, the minimum oil required for a leach-then-fill strategy is so small (7 million barrels for all Phase II caverns) that it is unlikely that leaching would ever have

Table 4 Leach Strategy Conversion Parameters*

Decision to Convert (from start) (Days)	Start of Oil Injection (Days)	Leaching Complete (Days)	Filling Complete** (Days)	Average Oil Fill Rate During Leach/Fill (MB/D)	Comments
290	520	1040	1120	12	L/F strategy
410	560	1040	1120	13	
530	630	1040	1120	16	
650	705	1040	1120	20	Conversions from L-T-F to L/F.
775	805	1040	1120	28	
NA	960	960	1205	NA	L-T-F strategy

* These numbers are based on a typical Bryan Mound cavern: brine production = 113 MD/D, sump delay = 60 days, contingency = 10%.

**Fill rate after completing leaching is 40 MB/D.

to be curtailed because of lack of oil. If oil does become available a leach-then-fill converted to a leach/fill will be able to accept oil at a faster rate than an interrupted leach/fill. However, once conversion has been exercised, the oil requirements are rigid. In the event oil deliveries are interrupted, leaching may have to stop.

The ability to convert from a leach-then-fill to a leach/fill strategy allows maintaining the capability of storing oil on relatively short notice while allowing the leaching to proceed. This flexibility is achieved at essentially no cost in terms of cavern completion time or cavern shape. The ability to convert from a leach/fill to a leacn-then-fill would provide valuable protection against interruption of oil delivery part of the way through the leach/fill phase. Unfortunately such a conversion may create misshapen caverns. In some cases it may be possible to continue some level of leaching and keep the perturbations to the cavern shape within acceptable limits. However, leach/fill to leach-then-fill conversions have not been simulated.

Mixed Strategies -- In the above discussion it has been assumed that all caverns will be leached with a single strategy. There is no reason why mixed strategies cannot be used, e.g., half of the caverns can be leached with a leach-then-fill strategy and the other half with a leach/fill strategy. There are almost 4000 different mixes for leaching the 28 caverns in the Phase II of SPR. If conversion of the leach-then-fill to leach/fill is included in the mix, the number of options is considerably larger.

Evaluation of the oil volume schedule for each option is not practical. However, the limits of what can be achieved by mixed strategies are easily defined. For combinations of leach/fill and leach-then-fill strategies (no conversions), the maximum available volume for oil storage will be less than or equal to the volume available with all the caverns in a leach/fill mode and greater than or equal to the volume available with all in a leach-then-fill mode. Likewise the minimum oil volume required to complete leaching will lie between the minimums for leach/fill and for leach-then-fill. For Phase II of SPR (Figure 1) the difference between the maximum available storage curves is relatively small. (less than 45 MMB at any given time), while the difference between the minimum required oil volumes is large (a maximum of 183 MMB).

Mixed strategies will not allow the matching of any selected oil volume curve that lies between the maximum available oil storage for a leach/fill strategy and the minimum required for a leach-then-f ill strategy. In general once a desired volume at a given time during the leaching of the first group of caverns is selected, the number of options that achieve the volume is quite limited. Hence the freedom to choose other volumes at other times is severely restricted. The same applies to the second group of caverns. Therefore mixed strategies usually can be selected that pass through two selected oil volumes: one volume during the leaching of the

Group 1 caverns and one during Group 2. For the most part, these two points will define the rest of the oil volume curve.

There is little point to try and catalog all the mixed strategies because there are so many. However, the anticipated oil deliveries to the SPR should always be under review to assure that the best strategy for accommodating the delivery can be selected.

<u>Oil Fill Rates</u> -- The oil flow rate data for the combined sites are plotted for a leach/fill strategy in Figure 4. These plots reveal that wildly fluctuating rates are needed to meet either the minimum required or the maximum allowable extremes. It may be be impractical to buy oil on such a schedule. However, the rate of oil purchases can be smoothed considerably by filling at rate in between the maximum allowable and minimum required. A possible rate schedule is shown in Figure 4, and its impact on the oil volume vs time is shown in Figure 5. Any rate schedule whose integral falls between the maximum available and minimum required curves shown on Figure 1 is acceptable. This applies for both leach/fill and leach-then-fill strategies.

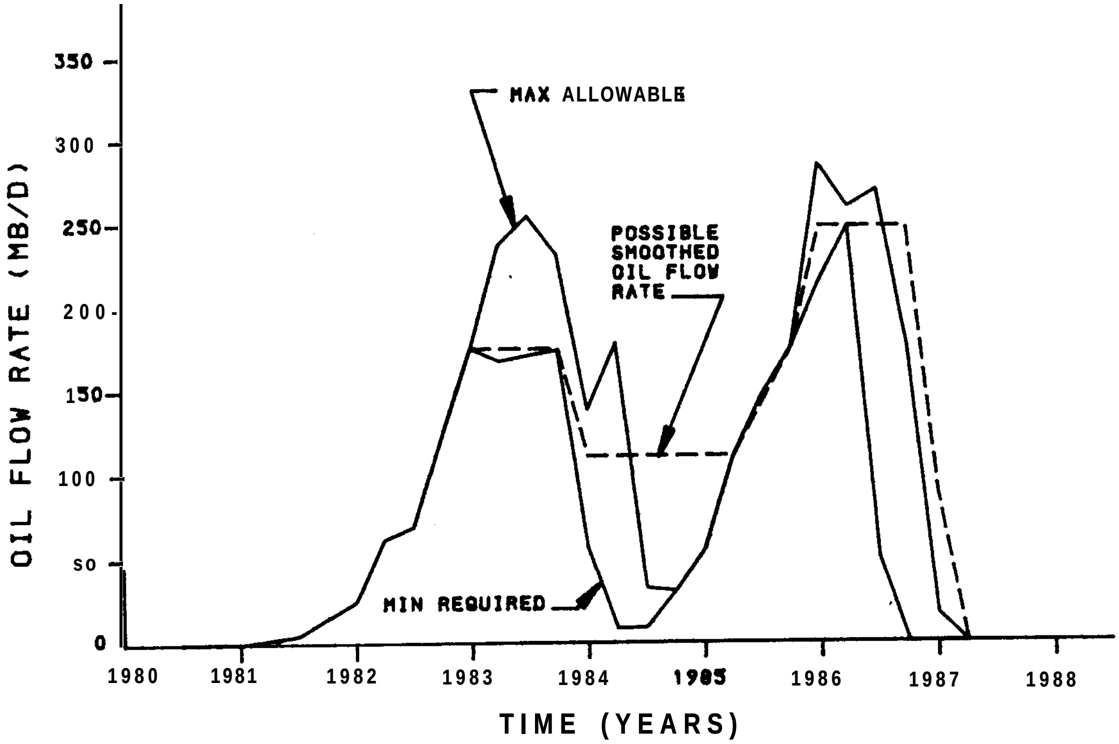

FIG 4 OIL FLOW RATE VERGUS TIME (LEACH/FILL)
BRYAN HOUND AND WEST HACKBERRY

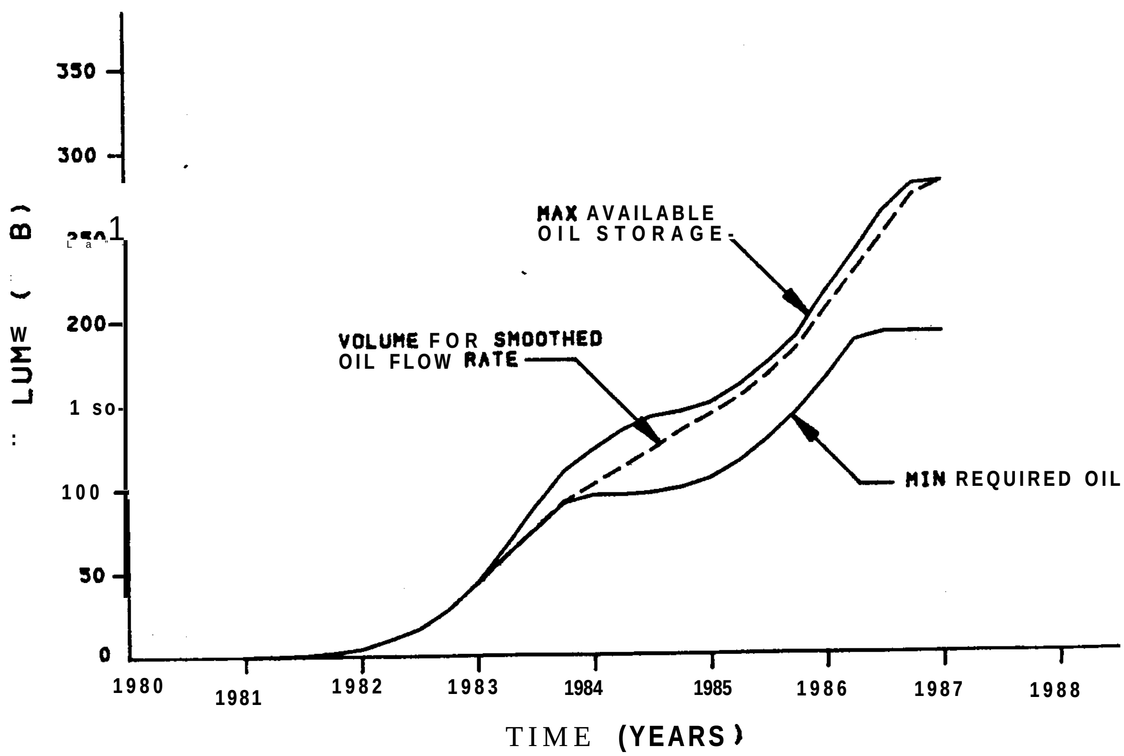

FIG 5 COMPARISON OF MAX/MIN OIL VOLUMES TO VOLUME
REGULTING FROM A SMOOTHED OIL FLOY RATE

Table 5 Overall Oil Volume Schedule for Phase II of SPR

Calendar Year	Qtr	Leach/Fill Total Leached* Volume (MMB)	Leach/Fill Oil Volume* (MMB) Min	Leach/Fill Oil Volume* (MMB) Max	Leach/Fill Oil Delivery** Rate MB/D Min	Leach/Fill Oil Delivery** Rate MB/D Max	Leach-Then-Fill Total Leached* Volume (MMB)	Leach-Then-Fill Oil. Volume* (MMB) Min	Leach-Then-Fill Oil. Volume* (MMB) Max	Leach-Then-Fill Oil Delivery** Rate MB/D Min	Leach-Then-Fill Oil Delivery** Rate MB/D Max
1980	1	0.4	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.0
	2	2.0	0.0	0.0	0.0	0.0	2.0	0.0	0.0	0.0	0.0
	3	6.1	0.0	0.0	0.0	0.0	6.1	0.0	0.0	0.3	0.0
	4	11.0	0.0	0.0	0.0	0.0	11.0	0.0	0.0	0.0	0.0
1981	1	16.7	0.2	0.2	2.2	2.2	16.7	0.1	0.1	1.0	1.0
	2	28.1	0.6	0.6	4.7	4.7	28.2	0.3	0.3	2.2	2.2
	3	42.8	2.0	2.0	14.7	14.7	43.1	0.6	0.6	3.5	3.0
	4	57.4	4.2	4.2	24.5	24.5	58.2	0.8	0.8	2.9	2.9
1982	1	75.3	9.8	9.8	61.7	61.7	76.6	1.3	1.3	5.8	5.8
	2	94.1	16.1	16.1	69.0	69.0	96.4	2.0	2.0	6.5	6.5
	3	112.9	27.4	27.4	123.6	123.6	116.7	2.5	2.5	6.1	6.1
	4	131.1	43.4	43.4	175.2	175.2	136.1	2.8	15.3	4.0	140.8
1983	1	148.5	58.7	65.1	167.7	237.8	155.0	3.2	25.4	3.3	110.3
	2	164.4	74.3	88.3	171.1	254.2	171.7	3.4	47.5	2.1	242.1
	3	178.6	90.2	109.4	174.0	231.1	187.2	3.5	66.6	1.9	209.4
	4	191.7	95.3	122.0	56.4	138.8	200.1	3.6	82.7	1.0	176.0
1984	1	205.0	95.6	138.3	3.1	178.1	214.7	3.9	98.9	2.9	177.9
	2	219.5	96.4	141.2	8.9	32.0	231.3	4.4	115.2	4.8	178.0
	3	237.5	99.2	144.0	30.3	30.3	250.8	5.0	131.4	7.3	177.6
	4	256.5	104.1	148.9	54.7	54.7	271.1	5.6	142.1	7.0	117.9
1985	1	275.6	114.3	159.1	111.0	111.0	291.4	6.1	142.6	5.1	5.1
	2	294.6	127.7	172.5	146.9	146.9	311.6	6.5	143.0	4.0	4.0
	3	312.8	143.7	188.5	174.7	174.7	328.9	6.8	162.8	3.1	216.8
	4	328.7	163.2	214.4	214.5	284.6	343.5	7.0	173.1	2.6	113.5
1986	1	341.8	185.8	237.9	247.6	258.0	344.4	7.0	209.7	0.2	401.0
	2	344.4	190.4	262.5	50.1	269.3	344.4	7.0	232.6	0.0	251.5
	3	344.4	190.4	278.5	0.0	175.0	344.4	7.0	248.6	0.0	175.0
	4	344.4	190.4	280.0	0.0	16.3	344.4	7.0	264.6	0.0	175.0
1987	1	344.4	190.4	280.0	0.0	0.0	344.4	7.0	280.0	0.0	168.9

* Volumes apply to the end of the given quarter, e.g., first quarter volumes are the volumes on March 31.
**Oil delivery rates are average values for the given quarter, e.g., first quarter rates are the average rates between January 1 and March 31.

Table 6 Oil Volume Schedule for Bryan Mound, Phase II

Calendar Year	Qtr	Leach/Fill Total Leached* Volume (MMB)	Leach/Fill Oil Volume* (MMB) Min	Leach/Fill Oil Volume* (MMB) Max	Leach/Fill Oil Delivery** Rate MB/D Min	Leach/Fill Oil Delivery** Rate MB/D Max	Leach-Then-Fill Total Leached* Volume (MMB)	Leach-Then-Fill Oil Volume* (MMB) Min	Leach-Then-Fill Oil Volume* (MMB) Max	Leach-Then-Fill Oil Delivery** Rate MB/D Min	Leach-Then-Fill Oil Delivery** Rate MB/D Max
1980	1	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	2	2.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	3	6.1	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0
	4	11.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1981	1	16.7	0.2	0.2	2.2	2.2	16.7	0.1	0.1	1.0	1.0
	2	23.4	0.6	0.6	4.7	4.7	23.5	0.3	0.3	2.2	2.2
	3	30.9	2.0	2.0	14.7	14.7	31.2	0.6	0.6	3.0	3.0
	4	38.4	4.2	4.2	24.5	24.5	39.2	0.8	0.8	2.9	2.9
1982	1	45.9	9.1	9.1	54.1	54.1	47.2	1.0	1.0	2.3	2.3
	2	53.3	14.5	14.5	58.9	58.9	55.1	1.2	1.2	1.6	1.6
	3	60.5	21.0	21.0	70.8	70.8	63.1	1.3	1.3	1.5	1.5
	4	67.1	29.4	29.4	91.8	91.8	70.2	1.4	13.9	1.1	137.9
1983	1	72.9	36.7	43.1	80.5	150.6	76.7	1.5	23.7	0.8	107.8
	2	78.2	40.8	54.8	45.0	128.1	81.6	1.5	45.6	0.0	240.0
	3	83.0	40.8	60.0	0.0	57.1	86.7	1.5	60.0	0.4	157.6
	4	88.4	40.9	60.1	1.4	1.4	92.5	1.6	60.1	1.0	1.0
1984	1	94.5	41.2	60.4	3.1	3.1	99.9	1.9	60.4	2.9	2.9
	2	101.9	42.0	61.2	8.9	8.9	107.7	2.2	60.7	3.0	3.0
	3	109.4	44.1	63.3	22.4	22.4	115.7	2.4	60.9	2.6	2.6
	4	117.0	48.1	67.3	44.6	44.6	123.7	2.6	61.1	2.0	2.0
1985	1	124.5	53.3	72.5	56.2	56.2	131.6	2.7	61.2	1.6	1.6
	2	131.8	59.1	78.3	63.5	63.5	139.5	2.9	61.4	1.5	1.5
	3	138.5	67.0	86.2	86.5	86.5	144.8	3.0	81.0	0.9	214.6
	4	143.8	74.9	100.5	87.0	157.1	147.6	3.0	91.1	0.5	111.4
1986	1	147.6	81.6	108.1	73.4	83.8	147.6	3.0	113.0	0.0	240.0
	2	147.6	81.6	120.0	0.0	129.9	147.6	3.0	120.0	0.0	76.5

* Volumes apply to the end of a given quarter.
**Oil delivery rates are average values for the given quarter.

Table 7 Oil Volume Schedule for West Hackberry, Phase II

Calendar Year	Qtr	Leach/Fill: Total Leached* Volume (MMB)	Leach/Fill: Oil Volume* (MMB) Min	Leach/Fill: Oil Volume* (MMB) Max	Leach/Fill: Oil Delivery** Rate (MB/D) Min	Leach/Fill: Oil Delivery** Rate (MB/D) Max	Leach-Then-Fill: Total Leached* Volume (MMB)	Leach-Then-Fill: Oil Volume* (MMB) Min	Leach-Then-Fill: Oil Volume* (MMB) Max	Leach-Then-Fill: Oil Delivery** Rate (MB/D) Min	Leach-Then-Fill: Oil Delivery** Rate (MB/D) Max
1980	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1981	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	2	4.7	0.0	0.0	0.0	0.3	4.7	0.0	0.0	0.0	0.0
	3	11.9	0.0	0.0	0.0	0.0	11.9	0.0	0.0	0.0	0.0
	4	19.0	0.0	0.0	0.0	0.0	19.0	0.0	0.0	0.0	0.0
1982	1	29.4	0.7	0.7	7.6	7.6	29.4	0.3	0.3	3.5	3.5
	2	40.8	1.6	1.6	10.1	10.1	41.3	0.8	0.8	4.9	4.9
	3	52.4	6.4	6.4	52.8	52.8	53.6	1.2	1.2	4.6	4.6
	4	64.0	14.0	14.0	83.4	83.4	65.9	1.4	1.4	2.9	2.9
1983	1	75.6	22.0	22.0	87.2	87.2	78.3	1.7	1.7	2.5	2.5
	2	86.2	33.5	33.5	126.1	126.1	90.1	1.9	1.9	2.1	2.1
	3	95.6	49.4	49.4	174.0	174.0	100.5	2.0	6.6	1.5	51.8
	4	103.3	54.4	61.9	55.0	137.4	107.6	2.0	22.6	0.0	175.0
1984	1	110.5	54.4	77.9	0.0	175.0	114.8	2.0	38.5	0.0	175.0
	2	117.6	54.4	80.0	0.0	23.1	123.6	2.2	54.5	1.8	175.0
	3	128.1	55.1	80.7	7.9	7.9	135.1	2.6	70.5	4.7	175.0
	4	139.5	56.0	81.6	10.1	10.1	147.4	3.0	81.0	5.0	115.9
1985	1	151.1	61.0	86.6	54.8	54.8	159.8	3.4	81.4	3.5	3.5
	2	162.8	68.6	94.2	83.4	83.4	172.1	3.6	81.6	2.5	2.5
	3	174.3	76.7	102.3	88.2	88.2	184.1	3.8	81.8	2.2	2.2
	4	184.9	88.3	113.9	127.5	127.5	195.9	4.0	82.0	2.1	2.1
1986	1	194.2	104.2	129.8	174.2	174.2	196.8	4.0	96.7	0.2	161.0
	2	196.8	108.8	142.5	50.1	139.4	196.8	4.0	112.6	0.0	175.0
	3	196.8	108.8	158.5	0.0	175.0	196.8	4.0	128.6	0.0	175.0
	4	196.8	108.8	160.0	0.0	16.3	196.8	4.0	144.6	0.0	175.0
1987	1	196.8	108.8	160.0	0.0	0.0	196.8	4.0	160.0	0.0	168.9

* Volumes apply to the end of the given quarter.
**Oil delivery rates are average values for the given quarter.

APPENDIX A

Leach Schedule Assumptions

The assumptions used to generate the baseline schedules are summarized below.

Leach Simulation - The leaching process was simulated using SALT 77 computer code developed by Ahmad Saberian. The leaching , schedules are designed to produce a total leached volume of 12.3 million barrels (10 million barrels for oil, 1 million for a brine buffer, and a 1.3 million sump for insolubles). The maximum diameter at the top is 230 feet, and the diameter 2000 feet below the top is 170 feet. For the most part the simulations assumed the three-well slick hole configuration at Bryan Mound. (In this configuration the three-wells are direct leached simultaneously until the sump/chimney is completed. At this point the inner tubing is removed from all three leaching strings; one of the wells is selected for raw water injection; and the other two are used for brine production.) Sufficient work has been done on other leaching strategies to indicate that the leaching configuration (one, two or three wells in either simultaneous or slick-hole modes) has little impact on either the total leached volume or the oil volume characteristics of the cavern if the brine production rates are the same for all configurations. Therefore the leaching configuration is not of concern in developing the leaching and oil fill strategies in this report.

The leaching schedules used in the simulations are summarized in Table A-l. Significant oil injection occurs during the second and third reverse stages of the leach/fill strategy. During this time, rate of oil injection increases from about 10 MB/D to 30 MB/D. The leach schedules in Table A-l are not unique. Alternative schedules, which significantly alter the lengths of the stages and possibly the oil injection rates, could be devised that will produce final cavern shapes just as acceptable as the results of the schedule in Table A-l. However, the total time to complete the cavern will not change significantly. Some of the other strategies are discussed in Appendix D.

The leach schedules were converted into a matrix of time and volume values (Table A-2). This time-volume matrix is fundamental to the analysis. The rest of this appendix discusses how workover times, start times, brine production rules, contingency factors and sump delays modify the times in this matrix.

The time points were selected to coincide with ends of stages or, in the case of leach/fill, with times during which the oil injection was constant. The oil volumes and total leached volumes are assumed to be linear with time between any two points of the matrix. In other words, the time volume matrix in Table A-2 defines a piecewise linear approximation of the leach schedule in Table A-l.

Table A-l Leaching Schedules*

Stage	Leach/Fill						Leach-Then-Fill				
	Time (Days) Inc.	Total	Oil Level (ft)	Injection Point (ft)	Production Point (ft)	Oil Inject Rate (MB/D)	Time (Days) Inc.	Total	Oil Level (ft)	Injection Point (ft)	Production Point (ft)
Sump	30	30	3600	4450	4100	0	30	30	3600	4450	4100
sump/ Chimney	130	160	2050	4300	2300	0	130	160	2050	4300	2300
Reverse 1	170	330	2050- 2150	2300	4100	0	100	260	2050- 2100	2700	4100
Reverse 2	200	530	2150- 2500	3100'	4100	150d @ 11.3 50d @ 12.8	280	540	2100- 2150	3500	4100
Reverse 3	185	715	2500- 3150	3800	4000	100d @ 16.0 85d @ 30.8	125	665	2150	3800	4000

*These schedules assune a brine production rate of 136,000 MB/D. The oil level, injection and production points are in feet below the surface and are consistent with Bryan Mound caverns. Where ranges of depths are noted, the level or points moved during that stage.

Table A-2 Leach Schedule Time and Volume Matrix*

Time (days)	Leach/Fill Oil Volume (MMB)	Leach/Fill Leached Volume (MMB)	Time (days)	Leach-Then-Fill Oil Volume (MMB)	Leach-Then-Fill Leached Volume (MMB)
0	0	0	0	0	0
160	0	2.6	160	0	2.6
330	0.25	5.7	260	0.07	4.5
530	2.6	9.3	330	0.12	5.8
610	3.9	10.6	400	0.16	7.1
665	5.2	11.4	540	0.21	9.8
715	6.8	12.3	665	0.25	12.3

*Brine production rate of 136,000 MB/D assumed.

Workover Times -The leach simulation discussed above includes no allowance for well workovers. The well workover schedule summarized in Table A-3 is appropriate for a three-well slick-hole configuration and is assumed for this report.

The oil volume will not change significantly during the workovers. However, the leached volume increases significantly during the workovers. When the cavern is shut down for workovers, the brine in the cavern is not saturated and continues to leach. If there is sufficient time to allow the brine to saturate, the leaching during the six workovers would add almost 900 MB to the volume. Unfortunately the model will not work when the brine production is set to zero. Therefore the effect of leaching during the workovers cannot be addressed directly. The preliminary leach schedule submitted by Sandia on July 30, 1980 was based on a leaching simulation where the brine in the cavern was set to saturation at the workover times without changing the volume. This simulation overestimates the time required to leach the cavern, because the leaching rate at the startup after a workover is retarded and the increase in volume necessary to saturate the brine (see Appendix D for further discussion of this simulation) is ignored. The approach used in this report assumes instantaneous workovers which result in no changes in either volumes or brine saturations. Furthermore, the simulation is stopped before the desired 12.3 MMB volume is reached. The total leaching time for this approach is about 25 days shorter than the preliminary version discussed above.

The workover times are added to the appropriate times in the time-volume matrix (Table A-2). The volumes remain unchanged. Furthermore constant rates of change in the leached and oil volumes are still assumed between each point in the time-volume matrix.

The workover times do depend on the leaching configuration to some extent because the number of wells which must be worked over varies. At the extreme a single-well configuration requires six well workovers and a three-well symmetric requires 18. Assuming five days per well workover, the total workover time could range between 30 and 90 days. The 58 days of workover used in this report is in mid-range, and it is felt that the ± 30 days caused by changes in configuration are not significant in a 1000 plus day leaching schedule.

Start Times - Of fundamental importance in deriving the schedule is the time when the leaching actually starts. In the case of Bryan Mound, the start dates for the Group 1 caverns are for the most part actual dates and, hence, there is little uncertainty. However, at one time the start date for Bryan Mound was scheduled to be December 17, 1980. Therefore the actual start slipped at least 90 days. Furthermore, full capacity was not achieved until 130 days after the start. The effect of a comparable slip in the start of West Hackberry is considered in Appendix B. The 60-day sump delay cited in this analysis should not be applied to delays in the start of leaching. This delay is meant to take into account problems encountered during the sump-chimney phase.

The start times for the Group 2 caverns are assumed to coincide with the completion of Group 1 caverns. The start dates for both groups are summarized in Table A-4. The effect of start time can be included in the time-volume matrix Table A-2 by starting leaching at some time other than zero and adding this time increment to all other times in the matrix.

Brine Production Rate - The schedules discussed above all are based on a brine production rate of 136 MB/D per cavern. In the case of Bryan Mound, this rate cannot be maintained because brine disposal for the site is limited to 680 MB/D or about 113 MB/D per cavern. The effect of reduced brine production was determined by performing simulations at brine production rates ranging from 85 to 136 MB/D per cavern. From these simulations a brine production factor was derived that would modify the time-volume matrix (Table A-2) for brine production rates other than 136 MB/D. This factor is given below.

$$B = \frac{(0.1575 - 2.08 \times 10^{-4} Q_o) Q_o}{(0.1575 - 2.08 \times 10^{-4} Q_i) Q_i}$$

where

B is the brine production factor which multiplies the times in Table A-2 to get the time appropriate for the reduced flow

Table A-3 Workover Schedule

Stage	Time Required
Midway through sump/chimney	12 days
End of sump/chimney	15 days
Midway through first reverse	5 days
End of first reverse	5 days
End of second reverse	5 days
End of third reverse	16 days
Total	58 days

Table A-4 Cavern Leaching Start Dates

		Bryan Mound	West Hackberry
Group 1		2 caverns on 3/10/80	8 caverns on 5/1/81
		4 caverns on 7/20/80	
Group 2	Leach/Fill		
		2 caverns on 1/12/83	8 caverns on 10/28/83
		4 caverns on 5/23/83	
	Leach-then-Fill		
		2 caverns on 10/27/82	8 caverns on 9/1/83
		4 caverns on 3/8/83	

Q_o is the design flow of 136 MB/D per cavern

Q_i is the reduced flow in MB/D per cavern.

The brine production factor is an average value applicable to the entire leaching schedule. In actuality, the brine production factor varies with the stage of leach. The factors for the sump and sump/chimney stages are somewhat smaller than the average, and those for the reverse stages are somewhat larger. Thus the average factor will give a slightly misshapen cavern of the right size. (This simplifying assumption will have a small impact on leaching schedules. However, in the actual leaching of the caverns it is probably desirable to adjust the times for each stage separately.)

Contingency Factor - All the times discussed to date are idealized times. They contain no allowance for equipment breakdowns, etc. A ten percent contingency factor is assumed in this analysis. This is accomplished by multiplying the times in Table A-2 or the times for a reduced brine production rate by 1.1. The workover times are also increased by ten percent.

Sump Delay - In addition to the contingency factor a 60-day delay is assumed during the sump/chimney. In other analyses of leaching schedules this was included to account for the problems peculiar to the start-up of a site. It was not applied to the startup of the Group 2 caverns because it was assumed that all the bugs would be eliminated by this time. However, based on the experience at Bryan Mound, the most important cause of delay during the sump/chimney phase is well plugups. The plugging problem is peculiar to the sump/chimney phase because the injection point is below the level of insolubles at the bottom of the cavern. When circulation is lost, a backflow of sand up the injection tube can plug it. Loss of circulation can be caused by bugs in the system encountered during startup, but it also can be caused by such events as loss of power to the site for a few seconds.

Table A-5 gives the histories of caverns 106 and 107 at Bryan Mound from the start of leach on March 10, 1980 through June 15, 1980. It is evident from this data that all the wells experienced plugups, but the length of time the well remains plugged varies drastically. This variation in time is not caused by more frequent plugging but rather by more severe plugs. (Well 106C plugged once and has resisted all efforts to unplug it.)

From this experience it is almost certain that wells will plug during the sump/chimney phase. Although the frequency of plugging may be somewhat less during the development of Group 2 caverns, it is doubtful that there will be any difference in severity. Therefore it seems appropriate to apply a sump delay of 60 days to the sump/chimney phase of both both Group 1 and 2 caverns.

Table A-5 Well Plugups Experience

Well No.	Total Days in Operation	Days with Flow	Days Plugged
106 A	97	91	6
B	97	91	6
C	97	13	84
107 A	97	92	5
B	97	61	36
C	97	82	16
Average	97	72	25

Summary of Time-Volume Matrix Modifications - The effects of workovers, brine production rates, start times, contingency factors and the startup delay are summarized in Table A-6, which illustrates how the time-volume matrix for the first two caverns at Bryan Mound were generated, and Table A-7 which gives the time matrices for all the caverns in Phase II. The oil volume and total leached volume matrices in Table A-2 remain the same.

Maximum Oil Fill Rate - The maximum oil fill rate for the site has no effect during the period when the caverns are being leached. The oil fill rate during leaching is derived from the time-volume matrices (Table A-7). However, when a cavern is completed, the remaining 3.2 MMB (9.75 MMB in the case of a leach-then-fill strategy) are added at the maximum oil fill rate minus any oil

Table A-6 Modification of a Time Leaching Matrix*

Basic Leach/Fill Time Matrix x 1.16 = (Table A-Z)	Matrix Modified for Reduced + Flow	Workover Time = (Table A-4)	Matrix Modified for Flow and x 1.1 = Workover	Matrix Modified for Flow, Work- + over, and Con-tingency	Start Time** and Sump = Delay	Final Matrix
0	0	0	0	0	70	70
160	186	27	213	234	130	364
330	383	37	420	462	130	592
530	615	42	657	723	130	853
610	708	42	750	825	130	955
665	772	42	814	895	130	1025
715	830	58	888	977	130	1107

* This is the time matrix for the two caverns at Bryan Mound which started leach on March 10, 1980 assuming a leach/fill strategy.
**Day zero is taken to be January 1, 1980; hence, the start date of March 10, 1980 is day 70.

Table A-7 Modified Time Matrices for the Baseline Case*

	Bryan Mound				West Hackberry	
	Group 1		Group 2		Group 1	Group 2
	2 Caverns	4 Caverns	2 Caverns	4 Caverns	8 Caverns	8 Caverns
Start Time (Days)	70	202	1107	1239	487	1397
	364	496	1401	1533	753	1663
End of Roof Dev.	592	724	1629	1.761	951	1861
	853	985	1890	2022	1176	2086
	955	1087	1992	2124	1264	2174
	1025	1157	2062	2194	1325	2235
End of Leach (Days)	1107	1239	2144	2276	1397	2307

*Day zero is January 1, 3.980; leach/fill strategy is assumed.

needed by caverns still being leached. Injection continues until the oil volume reaches 10 MMB. The fact that the brine production rate for the uncompleted caverns may have to be reduced to accommodate the brine produced by by the filling of the completed caverns is ignored. Usually this will be small perturbation in the overall leach schedule (Appendix E).

The maximum oil delivery rates (240 MB/D for Bryan Mound and 175 MB/D for West Hackberry) are the design maxima for the two sites. The attainable maximum delivery rates will be somewhat less.

Appendix B

Sensitivity Analysis

This appendix examines the sensitivity of the maximum available oil volume (leach/fill strategy) to changes in the assumed parameters. In particular, three cases are analyzed: the optimistic case, the delayed start at West Hackberry, and the small factor analysis case. The parameters assumed for these three cases are summarized in Table B-l. The optimistic case eliminates the 60-day sump delay and the 10 percent contingency that were assumed in the baseline case. The delayed start West Hackberry assumes that the experiences at Bryan Mound are repeated at West Hackberry: start of leach is delayed by 90 days and full capacity leaching is delayed by 220 days. The small factor analysis takes into account a number of minor factors that have been identified as affecting cavern development. The brine production at Bryan Mound is increased from 113 to 123 MB/D to take into account the effect of increasing the flow from 113 to 136 MB/D to five'caverns during the periods when one cavern is shut down for workovers (Appendix E). The maximum oil delivery rate at Bryan Mound is reduced from the maximum design rate of 240 MB/D to the maximum sustained rate of 180 MB/D. The sump delays for the Group 1 and Group 2 caverns at Bryan Mound are increased by 40 and 30 days respectively to account for the effects of adding 28 MMB of oil to the ESR caverns during the leaching of Group 1 and adding 19 MMB of oil to the Group 1 caverns during the leaching of Group 2 (Appendix E). At West Hackberry it

Table B-l
Sensitivity Analysis Cases

	Optimistic	Delay Start at West Hackberry	Small Factor Analysis
Brine Production Rate per Cavern	No change	No change	123 @ BM No change @ WH
Max Oil Delivery Rate to the Site	No change	No change	180 @ BM No change @ WH
Sump Delay (Days) (Group l/Group 2)	0/0	No change	100/90 @ BM 60/85 @ WH
Contingency (percent)	0/0	No change	No change
Start Dates	No change	No change @ BM 3 caverns delayed 90 days 5 caverns delayed 220 days @ WH	No change

is assumed that the ESR caverns are filled prior to start of leach of the Group 1 caverns, but 25 days are needed to account for the filling Group 1 caverns during the leaching of Group 2.

The combined maximum available oil storage for the three cases are compared to the baseline in Table B-2. Elimination of the sump delay and the contingency in the optimistic case has a very significant impact. Phase II of SPR is completed about nine months earlier than the baseline. In mid-1985 there are 70 MMB more oil in storage (25% of the entire Phase II capacity). One would expect that the actual performance would lie between the optimistic and the baseline. Unfortunately, the range is too broad to be of much use. The effect of delaying the start of leach at West Hackberry to match the experience at Bryan Mound also has a strong impact on the oil volume. If such a delay were to occur, the oil storage would lag by up to 27 MMB or about 10% of the Phase II capacity. There is no reason to believe that the experiences at Bryan Mound will apply to West Hackberry. The case is included to demonstrate the effect of delayed start. The minor perturbations to the leach schedule, which are included in the small factor analysis case, have a negligible effect on the oil volume. The maximum excursion of 5 MMB is less than two percent of the Phase II capacity. Since each of the perturbations is small and they are somewhat offsetting, the lack of impact is not surprising. On a technical basis, the small factor analysis should be a better prediction than the baseline. However, this introduces unnecessary complexity into the modeling.

Table B-2
Sensitivity Analysis Results

Year	Qtr	Baseline Oil Volume (MMB)	Incremental Chance in Baseline Oil Volume: Optimistic (MMB)	Delay of West Hackberry (MMB)	Small Factor Analysis (MMB)
1980	1	0.0	0.0	0.0	0.0
	2	0.0	0.0	0.0	0.0
	3	0.0	0.0	0.0	0.0
	4	0.0	0.2	0.0	0.0
1981	1	0.2	0.4	0.0	0.0
	2	0.6	1.7	0.0	-0.1
	3	2.0	3.1	0.0	-0.3
	4	4.2	7.0	0.0	-0.3
1982	1	9.8	8.6	-0.7	-0.1
	2	16.1	16.3	-1.3	0.3
	3	27.4	28.1	-5.6	0.9
	4	43.4	30.1	-10.8	2.2
1983	1	65.1	35.1	-14.6	1.5
	2	88.3	26.7	-18.4	1.5
	3	109.4	22.1	-25.2	0.0
	4	122.0	21.0	-25.6	0.0
1984	1	138.3	9.5	-27.2	0.1
	2	141.2	14.4	-13.6	0.5
	3	144.0	26.5	-.7	0.4
	4	148.9	38.8	-1.3	1.4
1985	1	159.1	54.8	-5.8	0.1
	2	172.5	69.6	-10.9	1.4
	3	188.5	73.9	-14.7	2.5
	4	214.4	63.9	-18.5	0.1
1986	1	237.9	42.1	-25.3	3.3
	2	262.5	17.5	-25.8	-5.0
	3	278.5	1.5	-27.3	-5.1
	4	280.0	0.0	-13.3	0.0
1987	1	280.0	0.0	0.0	0.0

Furthermore, inclusion of the perturbations presumes more accuracy for the model than is justified.

Based on a qualitative evaluation of the above cases on examination of the justification for the assumed values for some of the critical parameters, it is estimated that the accuracy of the predicted oil volumes is about $\pm$ 10% of the stored oil. Thus the oil volume may vary by $\pm$ 14 MMB toward the end of the leaching of Group 1 caverns and $\pm$ 28 MMB toward the end of leaching the second group. This accuracy does not include significant perturbations in the start date of West Hackberry or changes in the brine production rate.

Appendix C

Comparison of Predicted and Actual Performance

This appendix discusses techniques for comparing the predicted to the actual performance of leaching oil storage caverns. Also, the updating of the predictive model to take into account actual performance is considered. The use of these techniques is illustrated by comparing actual performance at Bryan Mound through 9/9/80 to the predicted performance.

The best measure of performance is the total leached volume. Table C-l gives the predicted total leached volume for the Group 1 caverns and for any single cavern at Bryan Mound.

The actual volume (in most cases computed from flow-rate and brine saturation measurements)[1] is compared in Figure C-l to the predicted volume for all Group 1 caverns at Bryan Mound. The predicted and measured volumes agree very well for the first 180 days. However, on a cavern by cavern basis the measured and predicted volumes do not agree as well as is illustrated by volume-time curves for caverns 106 and 107 in Figure C-2 and by Table C-2. Cavern 106 fell behind the predicted volume initially because one well was plugged for over 120 days. Cavern 107 was initially ahead of schedule, fell behind during the workovers and continues to lose ground. One well of cavern 107 was turned off because a sylvite band in the well was causing by abnormal cavern

Table C-l
Predicted Total Leached Volume for Bryan Mound Cavern
Using a Leach/fill Strategy*

Time (days)	Total Leached Volume (MMB) By Site** (day 0=1/1/80)	Total Leached Volume (MMB) By Cavern (day O=start of leach)
0.	0.0	.0
30.	0.0	.3
60.	0.0	.5
90.	.4	.8
120.	.9	1.1
150.	1.4	1.3
180.	1.9	1.6
210.	2.8	1.9
240.	4.4	2.1
270.	5.9	2.4
300.	7.5	2.7
330.	9.1	3.1
360.	10.7	3.5
390.	12.6	3.9
420.	14.4	4.3
450.	16.3	4.7
480.	18.2	5.1
510.	20.3	5.5
540.	22.8	6.0
570.	25.2	6.4
600.	27.7	6.8
630.	30.1	7.2
660.	32.6	7.6
690.	35.1	8.0
720.	37.5	8.4
750.	40.0	8.8
780.	42.5	9.3
810.	45.0	9.6
840.	47.5	10.0
870.	49.9	10.4
900.	52.3	10.8
930.	54.7	11.1
960.	57.2	11.5
990.	59.5	11.8
1010.	61.7	12.1
1050.	63.9	12.3
1080.	66.1	
1110.	68.1	
1140.	69.4	
1170.	70.8	
1200.	72.1	
1230.	73.4	
1260.	73.8	

* These predictions include 60-day sump delay, 10% contingency factor and 113 MB/D brine production.

** Only Group 1 caverns are included. Starts are the same as assumed in the baseline case.

Table C-2
Comparison of Measured and Predicted Cavern Volumes at Bryan Mound

Cavern	Leached Vol (MMB) as of 9-9-80 Predicted	Measured	Start of Leach Predicted	Actual	Days Ahead or (behind) Prediction	Comments
104	0.45	0.44	7-20-80	7-15-80	(2)	
105	0.45	0.38	7-20-80	7-16-80	(8)	
106	1.63	1.57	3-10-80	3-10-80	(6)	One well plugged for 127 days.
107	1.63	1.45	3-10-80	3-10-80	(20)	One well shut because of sylvite band.
108	--	0.24	--	7-17-80	--	Assumed to be a Group 2 cavern.
109	0.45	0.39	7-20-80	7-18-80	(7)	
110	0.45	0.99	7-20-80	3-17-80	60	Leaching started early in one well.
112	--	0.14	--	7-27-80	--	Assumed to be a Group 2 cavern.
TOTAL						
w/108 & 112	5.06	5.60			10	
w/o 108 & 112	5.06	5.22			3	

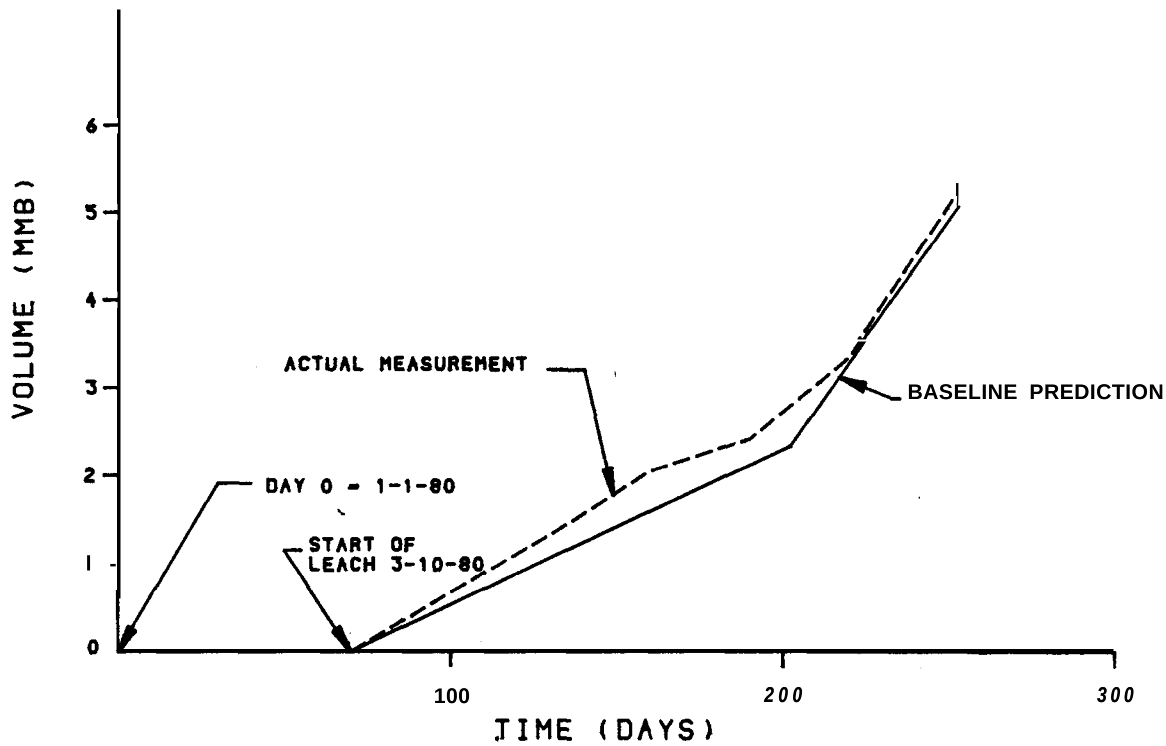

FIG C-I COMPARISON OF MEASURED AND PREDICTED CAVERN VOLUMES

BROUP 1 AT BRYAN HOUND

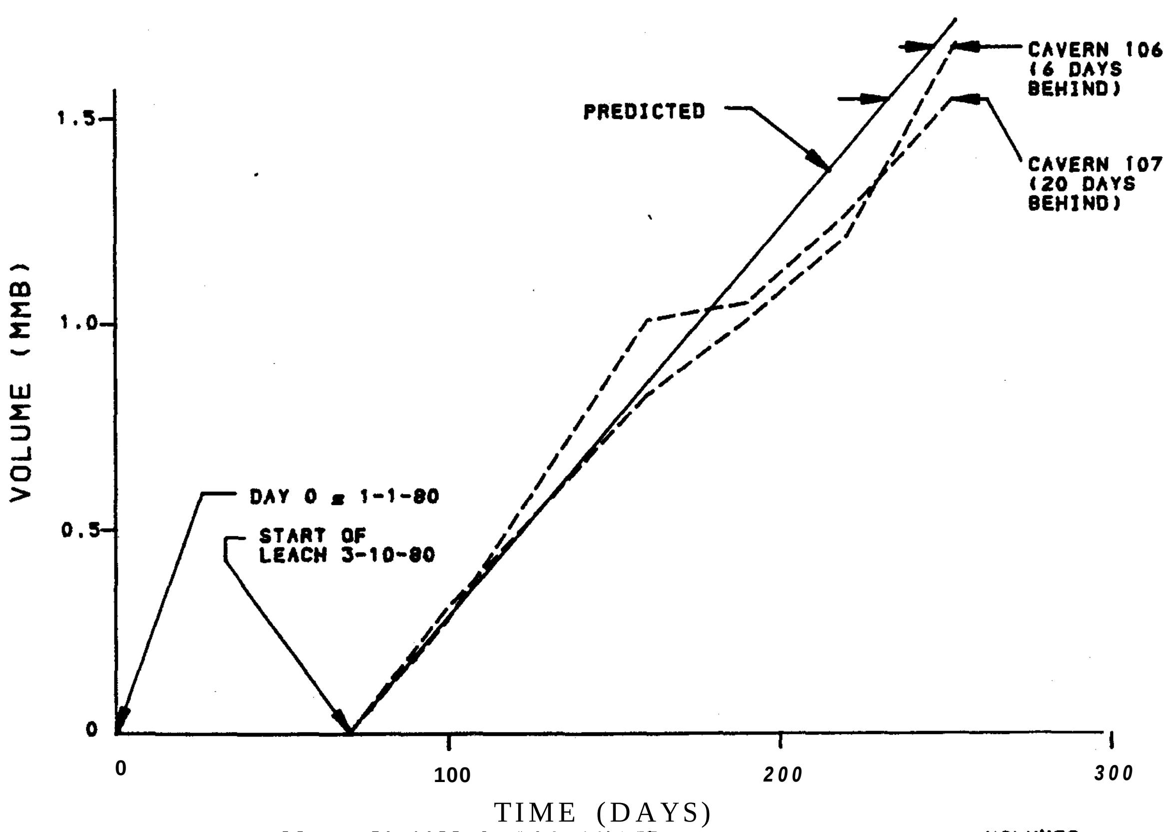

FIG C-2 COMPARISON OF MEASURED AND PREDICTED CAVERN VOLUMES

(CAVERNS 106 & 107 AT BRYAN MOUND)

growth. This well will remain turned off for the remainder of the sump/chimney phase.* Cavern 110 (Table C-2) is considerably ahead of schedule because leaching started in one well of the cavern on 3/17/80 while the model assumed a start date of 7/20/80. Furthermore, since eight caverns are being leached, two of them must be assumed to be Group 2 caverns. (Caverns 108 and 112 were chosen because they had the smallest leached volumes as of 9/9/80.) Inclusion of the volumes of these Group 2 caverns in the comparison of predicted and actual total leached volumes is not appropriate because the model assumes that leaching of Group 2 caverns will not commence until Group 1 is complete. The use of total leached volume to gage progress is valid only if the number of caverns being leached matches the number assumed in the predictive model.

For a predictive model to be useful it must be possible to incorporate past performance and expected future performance into the model to arrive at an updated and more accurate prediction. This has been done on a cavern by cavern basis for the Group 1

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*The measured volumes of caverns 106 and 107 were corrected to reflect the volumes measured during the sonar surveys of these caverns. The volumes determined by sonar are less than the volumes predicted from the flow and salinity measurements, because the sonared volumes do not include the leached volume that is filled with insolubles. The volumes calculated from flows and salinities do measure total leached volumes. Therefore the measured volume will be somewhat less than the total leached volume and somewhat more than the total free volume. Since the model assumes 10% insolubles, the predicted free volume is 90% of the total leached volume. Other than identifying the problem, no effort has been made to resolve the discrepancy.

caverns at Bryan Mound. The start times and the sump delay times for the updated prediction for the Group 1 caverns at Bryan Mound are summarized in Table C-3, and how the updated prediction varies from the baseline is given in Table C-4. The updated schedule (Table C-4) indicates that the performance at Bryan Mound can be expected to be ahead of schedule initially, fall behind but catch up and finish ahead of the baseline. However, the volume increments are less than the accuracy of the model. Therefore, the conclusion is that performance through 9/9/80 agrees with the baseline prediction.

The techniques used to derive the updated model are discussed below:

<u>Measured Leached Volumes Differ from Predicted Volumes:</u> The total leached volumes of all the Group 1 caverns (104, 105, 106, 107, 109, and 110) differ from their predicted volumes. This difference can be translated into days ahead or behind as illustrated in Figure c-2. If the actual rate of volume creation is expected to remain consistent with the predicted rate, the start time is modified to reflect the number of days ahead or behind. This is done for five of the caverns in Table C-2. (Cavern 107 is a special case and is discussed separately.)

<u>Expected Flow Rates During the Sump/Chimney are Different than those in the Baseline</u>: If the expected rate of volume creation during the sump/chimney phase is different from the rate assumed in the model,

Table C-3

Updated Start Times and Sump Delays
Based on Actual Performance
as of **9-9-80**

Cavern #	Start Date Baseline	Start Date Update	Sump Delay Baseline	Sump Delay Update
104	7-20-80	7-22-80	60	60
105	7-20-80	7-28-80	60	60
106	3-10-80	3-16-80	60	60
107	3-10-80	2-17-80	60	135
109	7-20-80	7-27-80	60	60
110	7-20-80	5-21-80	60	60

Table C-4
Comparison of Baseline Leaching of Group 1 Caverns
at Bryan Mound to an Updated Prediction*

	Total Leached Vol (MMB)		Oil Volume (MMB)			
			Minimum		Maximum	
	Total Baseline	Update Increment	Baseline	Update Increment	Baseline	Update Increment
1980-l	0.4	0.0	0.0	0.0	0.0	0.0
2	2.0	0.3	0.0	0.0	0.0	0.0
3	6.1	0.2	0.0	0.0	0.0	0.0
4	11.0	-0.1	0.0	0.0	0.0	0.0
1981-l	16.7	-0.3	0.2	0.0	0.2	0.0
2	23.4	-0.2	0.6	0.0	0.6	0.0
3	30.9	-0.3	2.0	-0.5	2.0	-0.5
4	38.4	-0.3	4.2	-0.1	4.2	-0.1
1982-l	45.9	-0.2	5.1	-0.1	9.1	-0.1
2	53.3	-0.1	14.5	-0.3	14.5	-0.3
3	60.5	-0.1	21.0	-0.5	21.0	-0.5
4	67.1	-0.1	29.4	-0.4	29.4	-0.4
1983-1	71.5	0.4	36.7	0.7	43.1	1.4
2	73.8	0.0	40.8	0.0	54.8	3.1
3	73.8	0.0	40.8	0.0	60.0	0.0

*Leach/fill strategy is assumed.

a more involved correction is required. The most likely cause for a variation in the rate of volume creation is expecting that one or more wells of a multiwell cavern will be shut in the future. In the case of cavern 107, well A will be shut in for the rest of the sump/chimney phase. Other causes of expected future shut ins including turning wells off because the drill string is so badly deviated that no useful sump would be created, and turning one or more wells off to allow the others to "catch up."

Both the start date and the sump delay value must be changed using the following equations:

$$T_o' = T_o - \Delta t + \left(\frac{T_o - t - \Delta t}{T_1 - t - \Delta t}\right)\left(\frac{Q_o - Q_1}{Q_o}\right)\Delta T \qquad \text{(Eq. C-1)}$$

$$\Delta D = \left(\frac{T_1 - T_o}{T_1 - t - \Delta t}\right)\left(\frac{Q_o - Q_1}{Q_o}\right)\Delta T \qquad \text{(Eq. C-2)}$$

Where T_o' is the updated start time

ΔD is the time increment (in days) to be added to the baseline sump delay to obtain the updated delay

T_o is baseline start time (day 70 for cavern 107)

T_1 is the baseline time of completion of the sump/chimney (day 364 for cavern 107)

t is the date of the actual measured leached volumes to which the model is being updated (9/9/80 or day 253 for cavern 107)

Δt is the number of days the cavern is ahead or behind prediction at time t (-20 days as of 9/9/80 for cavern 107)

Q_o is the baseline flow rate (113 MB/D for cavern 107)

Q_1 is the expected reduced flow rate (assumed to be 90 MB/D for cavern 107)

AT is expected time increment past the present time to that abnormal flow is expected to continue. (In the case of cavern. 107 the abnormal flow will continue until the sump/chimney is complete. It can be shown that:

$$\Delta T = \frac{Q_o}{Q_1} (T_1 - t - \Delta t)$$

Thus for cavern 107, AT is 164 days.

If the indicated values for cavern 107 are substituted into equations C-l and C-2, new start date is day 48 and the new sump delay value is 75 + 60 = 135 days. (The fact that the updated prediction assumes a start date earlier than the actual start date is an artifact of the modeling technique. Since the updated model is only intended to predict future performance, i.e., performance after **9/9/80,** this artificial start date causes no problems.

<u>Number of Caverns being Leached Differs from the Baseline</u>: The baseline assumes that 6 caverns are leached in Group 1 and followed by 6 in Group 2. If some other strategy is adopted the model has to be changed to reflect it. If on the other hand Group 2 caverns are only being leached when the Group-1 caverns cannot handle the available capacity for brine production, the impact will be less severe. Under the second assumption the Group 2 caverns will have a start date a few days prior to the completion of the Group 1 caverns. For instance, if caverns 108 and 112 are assumed to start as soon as caverns 106 and 107 are completed **(1/18/83** and **3/5/83** respectively), their start dates would be moved up by 27 and 16 days based on their volumes as of **9/9/80.** Thus incidental leaching of Group 2 caverns during the Group 1 phase has no impact on the Group 1 oil fill schedules. However, it will hasten the filling of Group 2 caverns.

<u>Brine Production During the Reverse Cycles Differs from the Baseline</u>: Once the reverse cycles start it may become evident that the brine production rate assumed in the baseline case is in error.

It will be necessary to update the brine production rate in the model. If the brine production rate is known it can be used. However, if an actual brine production rate is used, the contingency factor should be set to zero percent. Also the start date will have to be modified so that both the measured volume and the rate of creating volume can be matched at the date of interest.

References

[1]Daily Cavern Volumes Report prepared by DUCI.

Appendix D

Comparison of the Baseline Leaching Schedule With other Proposed Schedules

The baseline leaching schedules (Table A-l) are fundamental in this analysis. These schedules are by no means unique. In this appendix a number of other schedules, which have been suggested, are compared to the baseline. In all cases where the schedules can be tied to leaching simulations, the simulations were performed on computer codes developed by Ahmad Saberian. Therefore, the various leach schedules represent different applications of a single simulation technique. This discussion casts no light on the accuracy of that technique.

The leach schedules to be compared are summarized in Tables D-l and D-2, and their total leached volumes and oil volumes are plotted in Figures D-l and D-2. In the cases where workover times, sump delays and contingency factors are not specifically stated (Sandia #l and #2, and Saberian #l and #2), the values assumed for the baseline are used.

The alternative leach plans are discussed below:

Sandia #l and #2: The Sandia #l and #2 are the leach/fill and leach-then-fill plans, respectively, that were used in the preliminary version of the "SPR Leaching and Oil Fill Strategy.[1]

Table D-l
Leach Schedule Summaries for Various Leach/Fill Strategies*

	Baseline	Sandia #1	Saberian #1	Texas Brine #1	Texas Brine #2
Brine Prod. Rate	136 MB/D	136 MB/D	136 MB/D	113 MB/D	136 MB/D
Sump**	30 d @ 4450'	--	--	90 d @ 4500'	--
Sump/Chimney	130 d @ 4300'	200 d @ 4450'-4350'	230 d @ 4500'-4300'	90 d @ 4300'	140 d @ 5100'
1st Reverse	170 d @ 2300'	180 d @ 2300'	175 d @ 2300'	240 d @ 2400'	200 @ 3000'
2nd Reverse	200 d @ 3100	200 d @ 3100'	180 d @ 3100'	240 d @ 2750'	200 @ 3650'
3rd Reverse	185 @ 3800	165 d @ 3800'	170 d @ 3800'	240 d @ 3650'	150 @ 4450'
Total Time	715 days	745 days	755 days	900 days	690 days
Total Leached Volume	12.2 MMB	12.4 MMB	12.7 MMB	11.3 MMB	11.3 MMB
Oil Vol. @ end of Leach	6.8 MMB	5.9 MMB	6.1 MMB	8.2 MMB	7.0 MMB

* These are ideal leach schedules with no workover times or contingency allowances.
**Stages of the leaching give the time increment for the stage and the depth of the raw water injection point.

Table D-2
Leach Schedules Summaries for Various Leach-Then-Fill Strategies*

	Baseline	Sandia #2	Saberian #2
Brine Prod. Rate	136 MB/D	136 MB/D	136 MB/D
Sump**	30 d @ 44.50'	--	--
Sump/Chimney	130 d @ 4300'	200 d @ 4450'-4350'	230 d @ 4450'-4300'
1st Reverse	100 d @ 2700'	130 d @ 2700'	100 d @ 2700'
2nd Reverse	280 d @ 3500'	180 d @ 3500'	160 d @ 3100'
3rd Reverse	125 d @ 3800'	180 d @ 3800'	200 d @ 3500'
Total Time	665 days	690 days	690 days
Total Leached Volume	12.2 MMB	12.3 MMB	12.6 MMB

* These are ideal leach schedules with no workover times or contingency allowances.
**The stages of leaching give the time increment for the stage and the depth of the raw water injection point.

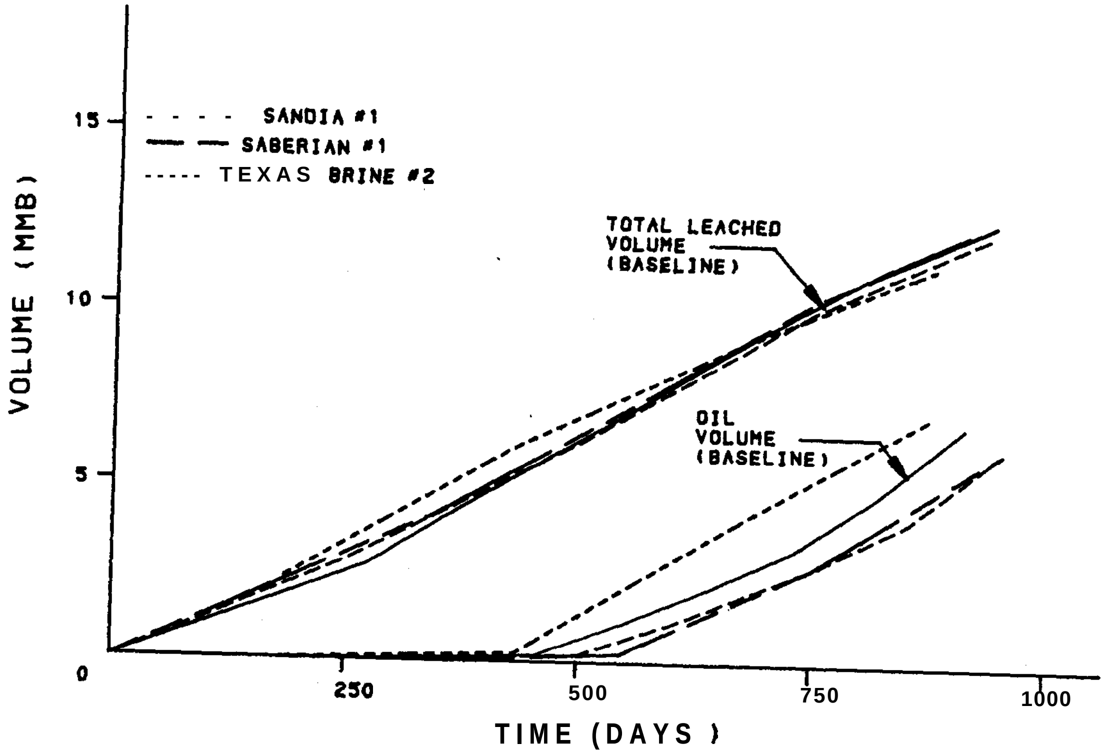

FIG D-l COMPARISON OF LEACH/FILL SCHEDULES
(136 MB/D BRINE PRODUCTION RATE,

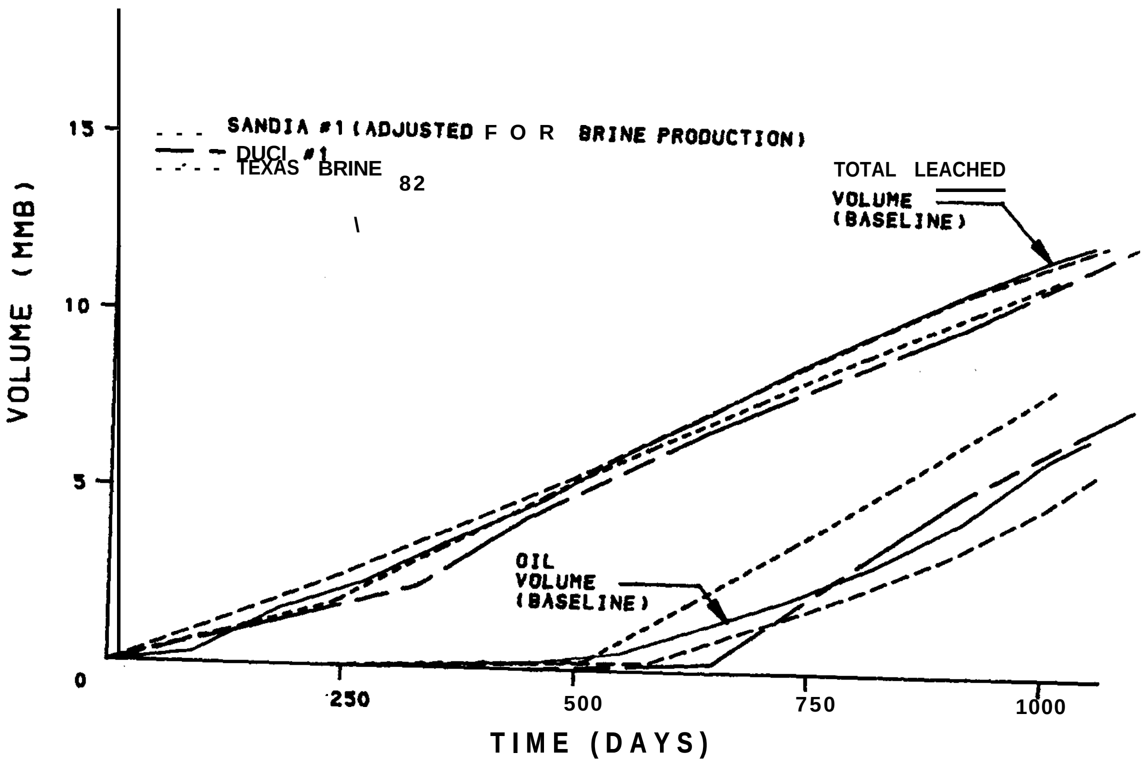

FIG D-2 COMPARISON OF LEACH/FILL SCHEDULES
(113 MB/D BRINE PRODUCTION RATE)

There are two significant differences between the baseline schedules and Sandia #1 and #2. The Sandia #1 and #2 a use 200 day sump/chimney stage which generates a sump that is between 300 and 400 MB oversize. Thus the 30-day sump followed by a 130-day sump/chimney phase used in the baseline is more appropriate. Secondly, the Sandia #1 and #2 modeling did not account for the growth of the cavern during workovers (Appendix A). Therefore the total leaching times were overestimated.

Saberian #1 and #2: The Saberian #1 and #2 were simulations performed by Ahmad Saberian for Sandia Laboratories of a symmetrical three-well leach/fill strategy and a slick-hole, three-well, leach-then-fill strategy.[2] The longer leach times for these schedules are probably due to their slightly oversized volumes (12.7 versus the desired 12.3). Also, the 230-day sump/chimney phase probably results in an oversized sump. Both the Saberian and the Sandia simulations result in a cavern whose dimensions are as close to the idealized "flower pot" as those of the baseline.

Texas Brine #1: The Texas Brine #1 simulates a two-well cavern at Bryan Mound.[3] The simulation was performed by Ahmad Saberian. Unlike the others, the flow rate for this simulation is 113 MB/D. However, the 900-day leaching time is significantly longer than the adjusted 830-day leaching time for the baseline. This is particularly true because the Texas Brine' volume is about 1.0 MMB undersized. Also, this schedule assumes a constant oil injection rate of about 17 MB/D starting at the end of the first reverse. This results in a cavern shape that deviates from the ideal "flower pot."

Texas Brine #2: The Texas Brine #2 simulates a one-well cavern at West Hackberry.[3] Again, the cavern appears to be 1 MMB undersized. A constant oil fill rate of 20 MB/D is assumed. However, in this case the final cavern shape very closely matches the design goal.

DUCI #1: The DUCI #1 schedule is presented in their operational leach/fill plan.[4] Unfortunately, the leach modeling from which the schedule was derived is not identified; therefore, only the volume versus time curve in Figure D-2 is available.

From Figures D-l and D-2 it is evident that the total leached volume curves agree quite well. The variation in the oil volume curves is much more pronounced. However, in most cases the variations can be explained by identifiable differences in leaching schedules. For instance, the lag in the oil volume curves for Sandia #1 and Saberian #1 is due mainly to the excessive sump leaching time. The oil volume of Texas Brine #1 is significantly ahead of the baseline because it does not contain a 10 percent contingency factor. (The contingency is assumed to be completely offset by increased brine production during cavern workovers.[3]) Texas Brine #2 does contain 10 percent contingency, but the assumed sump leaching, well workover times, and sump delay are significantly different. If these were adjusted to conform with baseline, the oil volume curve would be delayed about 80 days and would compare favorably with the baseline.

In summary, the various leaching schedules do differ from the baseline but in most cases these differences can be attributed to differences in assumptions. The similarity is not surprising because all but DUCI #1 are known to be based on simulations using Ahmad Saberian's leaching codes.

References

[1]H. C. Shefelbine, "SPR Leaching and Oil Fill Strategies," draft, Sandia National Laboratories, Albuquerque, NM 7/30/80.

[2]Simulations performed by Ahmad Saberian at Sandia National Laboratories' request. Simulations submitted 3/18/80.

[3]Letter from J. L. Gabriel, Texas Brine Corporation, to J. Powell, DUCI, dated 8/23/79.

[4]Leach/Fill Operational Plan, Bryan Mound Texas," prepared for DUCI, Inc., by PB-KBB Inc. dated 9/5/79.

Appendix E

Effect of Time-varying Brine Production

All the analyses up to this point have assumed that the brine production rate remains constant during the leaching of the cavern. In practice the brine production rate will vary considerably. Of particular interest are variations that last for a significant portion of the cavern leaching time. Examples of such variations include having one or more wells of a multiwell cavern plugged during sump/chimney development, increasing the flow from other caverns when one cavern is down for workover, or reducing the flow from Group 2 caverns because Group 1 caverns are being filled with oil.

Hypothetical brine production versus time curves are shown in Fig. E-l.

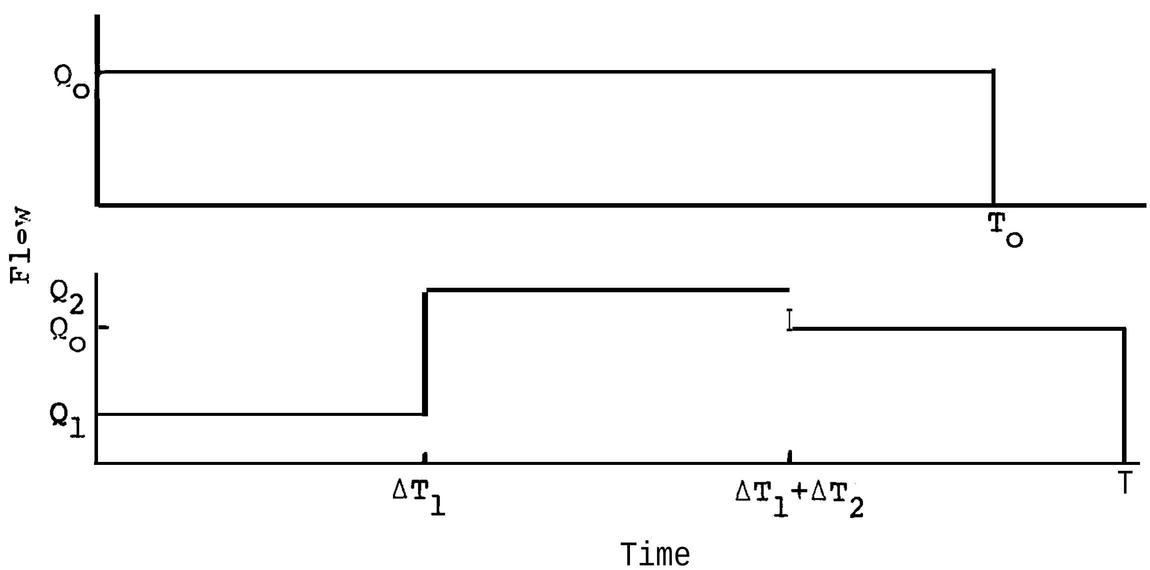

Figure E-l Brine Production versus Time Curves

It is assumed that at a constant brine production rate Q_o, the cavern will be completed in T_o days. The length of time, T, required to complete the same cavern under the varying brine production schedule shown in Figure E-l is desired. As a first approximation it can be assumed that quantity of brine produced in generating a cavern is a constant. (This is not exactly true because the saturation of the brine changes with brine production rate as discussed in Appendix A. However, the variation in saturation is a second order effect. Also the above assumption gives an upper bound on the effect of varying brine production.) Equating total brine production for the two cases in Figure E-l:

$$Q_o T_o = Q_1 \Delta T_1 + Q_2 \Delta T_2 + Q_o (T - \Delta T_1 - \Delta T_2)$$

Solving for the time increment introduced by the varying brine production $T-T_o$:

$$T-T_o = -\frac{Q_1-Q_o}{Q_o}\Delta T_1 - \frac{Q_2-Q_o}{Q_o}\Delta T_2$$

This can be generalized to an arbitrary number of variations in flow rate:

$$T-T_o = -\sum_{i=1}^{n} \frac{Q_i-Q_o}{Q_o}\Delta T_i$$

where T_o is the leaching required complete the cavern at the design flow rate Q_o.

T is the total leaching time required under time-varying flow conditions.

T_i is the time increment during which the brine production rate equals Q_i.

The above equation is used to calculate the impact of the following time-varying brine production situations.

. The brine production from Group 2 caverns will have to be reduced during the period of time that the Group 1 caverns are being filled with oil. (This also applies to delaying Group 1 caverns by the filling of ESR caverns.) Under the assumptions discussed above, it can be shown that the increase in leaching time, $T-T_o$ for the Group 2 caverns, is given by the total amount of oil injected into the Group 1 caverns divided by the total brine production rate for the site. The increase in leaching time for the Group 2 caverns is about 30 days if the Group 1 caverns are leach/filled and about 85 days if the caverns were leached-then-filled. The filling of the Group 1 caverns is most likely to occur during the sump-chimney development of the Group 2 caverns. Therefore the effect of the reduced brine production can be easily incorporated by adding the time increment, $T-T_o$, to sump delay of the Group 2 caverns.

. In multiwell caverns it is not unusual to have one or more of the wells plugged for significant periods of time during the sump/chimney development stage. The effect of this plugging on the cavern schedule can be determined by analyzing it as a reduction in brine production. For instance well C of cavern 106 was plugged for 127 days as of July 28, 1980. Assuming that this plugging reduces the brine production from 113 to 90 MB/D, cavern 106 should be 26 days behind schedule as of July 28. Based on measured volume it was 20 days behind. The effect of plugged wells can be easily incorporated into the schedule by adding the appropriate time increment, $T-T_o$, to the sump delay.

. During the workovdr of a cavern, the brine production rate for the other caverns can be increased if the site pumping and piping system will allow it. In the case of Bryan Mound the brine disposal permit to the gulf, 680 MB/D, is the limiting factor. Thus when six caverns are on line the brine production per cavern is limited to 113 MB/D, and when five are on line the flow can be increased to 136 MB/D. If it is assumed that caverns are down 60 days during their leaching for workovers and that the workovers are scheduled so that only one cavern is down at any one time, then the cavern leaching time is reduced by 60 days. Unlike the previous two cases the effect of workover will be spread out over the entire leaching process. Thus its effect should not be accommodated by subtracting 60 days from the sump delay. A better approach is to assume an average flow rate that will develop the cavern in the right amount of time. In this case a flow of 123 MB/D will be correct.

Appendix F

Computer Program Description

A computer program has been developed that automates the process described in Appendix A for creating leaching and oil fill predictions for SPR. Samples of the input (Fig. F-l) and the output (Fig. F-2) are given. The source listing for the program is given in Fig. F-3. The program is written in FORTRAN and run on the Sandia time share system. The major functions of the program are described briefly below.

Data Input

The time-volume matricies (Table A-2) for both leach/fill and leach-then-fill are stored in the program in the form of data statements. The workover times to be added to the time matrices (column 3 in Table A-6) are also stored internally. Other leaching strategies can be examined by replacing these four data statements. The remainder of the required input data is entered by the user at the start of execution. These are shown in Fig. F-l and described below.

- Select leach strategy: Either of the two internally stored leach strategies, leach/fill or leach-then-fill, can be selected. The selected strategy is used in all subsequent calculations.

- Select time step: The time step determines at what time interval the total leached volume, the oil volumes and the oil delivery rates will be calculated. Up to 71 time increments and volumes can be stored. Therefore the time step must be selected so that the maximum time encountered during execution is less than the maximum time that can be stored.

- Select the number of leach histories: From 1 to 12 different leach histories can be selected. These histories will all use the common strategy selected above, but they can have different start dates, delays, contingencies or brine production rates.

- Select maximum oil delivery rate: This is the rate at which oil can be delivered to the site for filling caverns after leaching has been completed. It has no effect on the oil delivery rate during the leaching process.

For each of the selected number of leach histories the user must enter the following information:

- Number of caverns: If more than one cavern has identical start times, delays, contingencies and brine production rate, only a single entry is needed.

- Start time: It is usually best to select zero time to coincide with a particular date. (In most of the above analyses l-l-80 was selected as zero time.) All start dates are then keyed to

- the selected zero time, e.g., 3-10-80 corresponds with a start time of day 70.

- Sump delay, contingency and brine production rate: All these factors are discussed in Appendix A. The selected brine production rate should be kept between 85 and 136 MB/D. Values outside this range can be selected, but the accuracy of the results may be degraded.

Calculation of Modified Time Matrices: The program takes all the input data and calculates a modified time matrix for each leach history using the procedure outlined in Table A-6. The resultant matrices are printed in the same order as which they were entered (Fig. F-2).

Calculation of Volumes and Rates During Leach: Using the modified time matrix and the internally stored volume matrices the program calculates the total leached volume and oil volume at integer multiples of the selected time step. The time starts at zero and goes to a maximum of 70 times the selected time step. The volumes are assumed to vary linearly with time between any two points in the time-volume **matricies.** The contribution of each history is computed and summed to give the total for the site. Once the oil volumes at each time are calculated, the rate of oil delivery at any given time is calculated by subtracting the volume at the immediately preceding time from the volume at the given time and dividing by the time step. The oil delivery rates calculated at this stage may exceed the specified maximum delivery rates. If this occurs leaching must be slowed. The oil volumes and rates calculated during the leaching phase correspond to the minimum volumes and rates shown in Fig. F-2.

Calculation of Volumes and Rates after Completing Leaching: At the end of leaching the caverns are not filled to capacity. Using the maximum oil delivery rate the caverns are filled to their design capacity. The leach history with the earliest completion date is selected. This cavern (or caverns) is filled at the maximum oil delivery rate minus any oil delivery required to complete the leaching of the other caverns. This continues until the selected cavern is full. The same procedure is repeated with the other caverns. The start of final filling of the second or subsequent caverns cannot commence before leaching has been completed and before the first or prior caverns have been filled. Once all the caverns are filled to capacity, a new set of oil delivery rates is calculated using the same algorithm described above. The oil volumes and delivery rates correspond to the maximum volumes and rates in Fig. F-2.

output: In addition to the terminal output, the data is written to a data file. On this file values at all 71 time steps are recorded. This data file simplifies the creation of leach schedules for multiple sites.

The program is designed to calculate the leaching schedule for a single site with all caverns being leached with a single leach strategy. However, by performing multiple executions and by developing a simple program to manipulate the data files, the program has been used to calculate combined leaching schedules for two or more sites. The same techniques could be used to examine the effect leaching some of the caverns at site with a leach/fill strategy and the remainder with a leach-then-fill strategy.

Fig. F-l User Supplied Data Entries
(Baseline values for Groups 1 and 2 at Bryan Mound)

```
ENTER LEACH STRATEGY (L/F=1,L-T-F=2) ? 1
           DESIRED TIME STEP (DAYS)? 91.25
    NUM OF DIFFERENT LEACH HISTORIES? 4
        MAX OIL DELIVERY RATE (MB/D) ? 240

FOR LEACH HISTORY  1
  ENTER NUM OF CAVERNS ? 2
      START TIME(DAYS) ? 70
      SUMP DELAY(DAYS) ? 60
  CONTINGENCY(PERCENT) ? 10
 BRINE PROD RATE(MB/D) ? 113

FOR LEACH HISTORY  2
  ENTER NUM OF CAVERNS ? 4
      START TIME(DAYS) ? 202
      SUMP DELAY(DAYS) ? 60
  CONTINGENCY(PERCENT) ? 10
 BRINE PROD RATE(MB/D) ? 113

FOR LEACH HISTORY  3
  ENTER NUM OF CAVERNS ? 2
      START TIME(DAYS) ? 1 ICI /
      SUMP DELAY(DAYS) ? 60
  CONTINGENCY( PERCENT) ? 10
 BRINE PROD RATE(MB/D) ? 1 13

FOR LEACH HISTORY  4
  ENTER NUM OF CAVERNS ? 4
      START TIME( DAYS) ? 1239
      SUMP DELAY( DAYS ) ? 60
  CONTINGENCY(PERCENT) ? 10
 BRINE PROD RATE( MB/D) ? 1 13
```

Fig. F-2 Sample Output
(Baseline Groups 1 and 2 at Bryan Mound)

LEACH TIME MATRICES

START TIME	END OF SUMP/CHIM	END OF HOOF DEV				END OF LEACH
70.	364.	592.	853.	955.	1025.	1107.
202.	496.	724.	985.	1087.	1157.	1239.
1107.	1401.	1629.	1890.	1992.	2062.	2144.
1239.	1533.	1761.	2022.	2124.	2194.	2276.

TIME (DAYS)	CAV VOL (MMB)	OIL VOL (MMB) MIN	OIL VOL (MMB) MAX	OIL RATE(MB/D) MIN	OIL RATE(MB/D) MAX
0.	0.0	0.0	0.0	0.0	0.0
91.	.4	0.0	0.0	0.0	0.0
183.	2.0	0.0	0.0	0.0	0.0
274.	6.1	0.0	0.0	0.0	0.0
365.	11.0	.0	.0	.0	.0
456.	16.1	.2	.2	2.2	2.2
548.	23.4	.6	.6	4.7	4.7
639.	30.9	2.0	2.0	14.7	14.7
730.	38.4	4.2	4.2	24.5	24.5
821.	45.Y	9.1	9.1	54.1	54.1
913.	53.3	14.5	14.5	58.9	58.9
1004.	60.5	21.0	21.0	70.8	70.8
1095.	67.1	2Y.4	2Y.4	91.8	91.8
1186.	72.9	36.7	43.1	80.5	150.6
1278.	78.2	40.8	54.8	45.0	128.1
1369.	83.0	40.8	60.0	0.0	57.1
1460.	88.4	40.9	60.1	1.4	1.4
1551.	Y4.5	41.2	60.4	3.1	3.1
1643.	101.9	42.0	61.2	8.9	8.9
1134.	109.4	44.1	63.3	22.4	22.4
1825.	117.0	48.1	67.3	44.6	44.6
1916.	124.5	53.3	72.5	56.2	56.2
2008.	131.8	59.1	78.3	63.5	53.5
2099.	138.5	67.0	86.2	86.5	86.5
2190.	143.8	'74.9	100.5	87.0	157.1
2281.	14'7.6	81.6	108.1	73.4	83.8
2373.	147.6	81.6	120.0	0.0	129.9

Fig. F-3 Source Program Listing

```
      PROGRAM OILF(INPUT,OUTPUT,TAPE1)
      DIMENSION TMOD(12,7),TOIL(14,71),TCAV(71),
     1STRT(12),SC(12),SMC(12),SLR(12),RATE(2,71),FAC(12),
     2OILV(2,8),CAV(2,8),TIME(2,7),WOVT(2,6)
C     DATA ENTRIES      .     .     .
      DATA (OILV(1,I),I=1,8)/0.0,0.0,0.25,2.6,3.9,5.2,6.8,10./
      DATA (CAV(1,I),I=1,8)/0.0,2.6,5.7,9.3,10.6,11.4,12.3,12.3/
      DATA (TIME(1,I),I=1,7)/0.0,160.,330.,530.,610.,665.,715./
      DATA (WOVT(1,I),I=1,6)/27.,37.,42.,42.,42.,58./
      DATA (OILV(2,I),I=1,8)/0.0,0.0,0.07,.12,.16,.21,.25,10./
      DATA (CAV(2,I),I=1,8)/0.0,2.6,4.5,5.8,7.10,9.80,12.3,12.3/
      DATA (TIME(2,I),I=1,7)/0.0,160.,260.,330.,400.,540.,665./
      DATA (WOVT(2,I),I=1,6)/27.,37.,37.,37.,42.,58./
      PRINT*,"    ENTER LEACH STRATEGY (L/F= 1,L-T-F=2)",
      READ*,LI
      PRINT*,"               DESIRED TIME STEP (DAYS)",
      READ*, DLT
      PRINT*, "       NUM OF DIFFERENT LEACH HISTORIES",
      READ*,NCAV
      PRINT*,"            MAX OIL DELIVERY RATE (MB/D)",
      READ*,RMAX
      DO 90 I=1,NCAV
      PRINT 600, I
  600 FORMAT(//," FOR LEACH HISTORY", I3)
      PRINT*,"  ENTER NUM OF CAVERNS",
      READ*,FAC(I)
      PRINT*,"      START TIME(DAYS)",
      READ*,STRT(I)
      PRINT*,"      SUMP DELAY( DAYS)",
      READ*,SC(I)
      PRINT*, "  CONTINGENCY(PERCENT)".
      READ*, SMC(I)
      SMC(I)=SMC(I)/100.+1.
      PRINT*, " BRINE PROD RATE( MB/D) ",
   90 READ*,SLR(I)
C     CALCULATE THE MODIFIED TIME MATRIX
      DO 21 K=1,NCAV
      RFAC=BPR(SLR(K))
      TMOD(K,1)=TIME(LI,1)+STRT(K)
      DO 20 I=2,7
      I1=I-1
   20 TMOD(K,I)=TMOD(K,I1)+SC(K)+SMC(K)*(TIME(LI,I)*RFAC+WOVT(LI,I1))
   21 CONTINUE
C     CALCULATE VOLUMES AND RATES DURING LEACH
      T=0.1
      DO 30 J=1,71
      TOIL(13,J)=0.
      TCAV(J)=0.
      DO 40 K=1, NCAV
      IF(T.GT.TMOD(K,7)) GO TO 41
      IF(T.LT.TMOD(K, 1)) TOIL(K,J)=0.
      DO 35 L=1,7
      IF(T.GE.TMOD(K,L).AND.T.LE.TMOD(K,L+1)) GO TO 36
      GO TO 35
   36 DT=(T-TMOD(K,L))/(TMOD(K,L+1)-TMOD(K,L))
```

Fig. 3 (continued)

```
      TOIL(K,J)=(OILV(LI,L)+(OILV(LI,L+1)-OILV(LI,L))*DT)*FAC(K)
      TOIL(13,J)=TOIL(13,J)+TOIL(K,J)
      VC=CAV(LI,L)+(CAV(LI,L+1)-CAV(LI,L))*DT
      TCAV(J)=TCAV(J)+(CAV(LI,L)+(CAV(LI,L+1)-CAV(LI,L))*DT)*FAC(K)
   35 CONTINUE
      GO TO 40
   41 TOIL(K,J)=OILV(LI,7)*FAC(K)
      TOIL(13,J)=TOIL(13,J)+TOIL(K,J)
      TCAV(J)=CAV(LI,8)*FAC(K)+TCAV(J)
   40 CONTINUE
   30 T=T+DLT
      RATE(1,1)=0.0
      DO 70 L=2,71
   70 RATE(1,L)=(TOIL(13,L)-TOIL(13,L-1))/(0.001*DLT)
C     CALCULATE VOLUMES AND RATES AFTER LEACH COMPLETION
      TMIN=10000.
      DO 81 JA=1,NCAV
      IF(TMIN.LT.TMOD(JA,7)) GO TO 81
      TMIN=TMOD(JA,7)
      IMIN=JA
   81 CONTINUE
      JM=2+INT(TMIN/DLT)
   92 IF(RATE(1,JM).LT.RMAX)GO TO 91
   93 JM=JM+1
      IF(JM.GT.70) GO To 800
      TMIN=DLT*FLOAT(JM-2)
      GO TO 92
   91 T1=(OILV(LI,8)*FAC(IMIN)-TOIL(IMIN,JM))*1000./(RMAX-RATE(1,JM))
      T2=T1+TMIN
      TJM1=DLT*FLOAT(JM-1)
      IF(T2.LE.TJM1) GO TO 45
      TOIL(IMIN,JM)=TOIL(IMIN,JM)+(TJM1-TMIN)*(RMAX-RATE(1,JM))/1000.
      JM2=JM+1
      DO 2 KL=JM2,71
    2 TOIL(IMIN,KL)=TOIL(IMIN,JM)
      GO TO 93
   45 CONTINUE
      DO 1 IA=JM,71
    1 TOIL(IMIN,IA)=OILV(LI,8)*FAC(IMIN)
      TMOD(IMIN,7)=1000.*TMOD(IMIN,7)
      TMIN=T2
      TMIN1=10000.0
      DO 31 JB=1,NCAV
      IF(TMIN1.LT.TMOD(JB,7)) GO TO 31
      IMIN=JB
      TMIN1=TMOD(JB.7)
   31 CONTINUE
      IF(TMIN1.GE.9999.) GO TO 800
      IF(TMIN1.GE.TMIN) TMIN=TMIN1
      JM=2+INT(TMIN/DLT)
      GO TO 92
  800 TX=2.+(TMIN/DLT)
      MAX=INT(TX)
      DO 95 I=1,71
      TOIL(14,I)=0.
```

Fig. 3 (continued)

```
      DO 96 M=1,NCAV
   96 TOIL(14,I)=TOIL(14,I)+TOIL(M,I)
   95 CONTINUE
      DO  80  L=1,NCAV
   80 TMOD(L,7)=TMOD(L,7)/1000.
      RATE(2,1)=0.0
      DO 75 K=2,71
   75 RATE(2,K)=(TOIL(14,K)-TOIL(14,K-1))/(0.001*DLT)
C     PRINT RESULTS
   18 PRINT 650
  650 FORMAT(//* LEACH TIME MATRICES*/
     16X,*START*4X*END OF*7X*END OF*36X*END OF*/
     26X,*TIME*4X*SUMP/CHIM*5X*ROOF DEV*35X*LEACH*)
      DO 50 J=1,NCAV
   50 PRINT 100,(TMOD(J,I),I=1,7)
  100 FORMAT(/F11 .0)
      PRINT 200
      DO 61 J=1,71
      DAY=DLT*FLOAT(J-1)
   61 WRITE(1,301)DAY,TCAV(J),TOIL(13,J),TOIL(14,J),RATE(1,J),RATE(2,J)
      DO 60 J=1,MAX
  200 FORMAT(//* TIME*5X*CAV VOL*8X*OIL VOL (MMB)*8X*OIL RATE(MB/D)*/
     11X,*(DAYS)*5X*(MMB)*9X*MIN*6X*MAX*10X*MIN*6X*MAX*)
      DAY=DLT*FLOAT(J-1)
   60 PRINT 300,DAY,TCAV(J),TOIL(13,J),TOIL(14,J),RATE(1,J),RATE(2,J)
  300 FORMAT(1X,F6.0,4X,F6.1,7X,F6.1,3X,F6.1,7X,F6.1,3X,F6.1)
  301 FORMAT( 1X,6F6.1)
      END
C     CALCULATE LEACH RATE FACTOR
      FUNCTION BPR(F)
      F0=136.
      A=-2.08E-04
      B=0.1575
      BPR=((A*F0+B)*F0)/((A*F+B)*F)
      RETURN
      END
```

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